National Aeronautics and
Space Administration
Goddard Space Flight Center
Greenbelt, MD 20771

Reply to Attn of: **Hydrological Sciences Branch, Code 974**

March 21, 2000

TO: MDAR
Code Y
4000 Virginia Avenue, SW, Suite 700
Washington, DC 20024

RE: **A Global Land-surface Data Assimilation Scheme (GLDAS)**, a proposal submitted to the NASA-ESE Modeling and Analysis Research Announcement NRA-99-OES-04 by P. Houser, H. L. Pan, K. Mitchell, M. Bosilovich, J. Walker, B. Cosgrove, and J. Entin

Dear Sir/Madam,

Enclosed please find a proposal in response to the FY 2000 NASA research announcement NRA 99-OES-04 addressing NASA-ESE Modeling and data analysis research. This proposal primarily relates to the program element (F) *EOS Interdiciplinary Science Program (EOS/IDS)*. The contact person identified in the program announcement is J. Dodge.

If you have any questions regarding this proposal or other matters, please do not hesitate to contact any of the investigators. We are looking forward to hearing back from you so that we may proceed with the critical work outlined in this proposal.

Sincerely yours,

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A Global Land Data Assimilation Scheme (GLDAS)

Submitted to NRA-99-OES-04: NASA-ESE Modeling and Data Analysis Research, EOS/IDS

Paul R. Houser, Michael Bosilovich, Brian Cosgrove, Jared K. Entin, and Jeffrey Walker

NASA's Goddard Space Flight Center(GSFC), Hydrologic Sciences Branch; Greenbelt, MD 20771

Hua-Lu Pan and Kenneth Mitchell

NOAA's National Centers for Environmental Prediction(NCEP), Camp Springs, MD 20746

Proposal Cover Sheet

Proposal No. _____________

Title: **A Global Land Data Assimilation (GLDAS)**

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Institution: National Aeronautics and Space Administration; Goddard Space Flight Center

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NASA/GSFC Budget: 1st Year: $288,299 2nd Year: $285,860 3rd Year: $287,506 **Total:** $861,664

Certification of Compliance with Applicable Executive Orders and U.S. Code

By submitting the proposal identified in this *Cover Sheet/Proposal Summary* in response to this Research Announcement, the Authorizing Official of the proposing institution (or the individual proposer if there is no proposing institution) as identified below:

- certifies that the statements made in this proposal are true and complete to the best of his/her knowledge;
- agrees to accept the obligations to comply with NASA award terms and conditions if an award is made as a result of this proposal; and
- confirms compliance with all provisions, rules, and stipulations set forth in the two Certifications contained in this NRA [namely, (i*) Certification of Compliance with the NASA Regulations Pursuant to Nondiscrimination in Federally Assisted Programs, and (ii) Certifications, Disclosures, And Assurances Regarding Lobbying and Debarment & Suspension*].

Willful provision of false information in this proposal and/or its supporting documents, or in reports required under an ensuing award, is a criminal offense (U.S. Code, Title 18, Section 1001).

Title of Authorizing Institutional Official: Dr. Vincent V. Salomonson, Director of Earth Sciences

Signature: ______________________________ Date: ______________________________

Name of Proposing Institution: NASA Goddard Space Flight Center

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Proposal Summary

Objectives and Justifications

Accurate initialization of land surface moisture and energy stores in fully-coupled climate system models is critical for meteorological and hydrological prediction from days to seasons because of their regulation of surface water and energy fluxes between the surface and atmosphere over a variety of time scales. Because these are integrated states, errors in land surface forcing and parameterization accumulate in land surface stores, which leads to incorrect surface water and energy partitioning. However, many innovative new land surface observations are becoming available that may provide additional information necessary to constrain the initialization of land surface states critical for long-term prediction. These constraints can be imposed in two ways. Firstly, by forcing the land surface primarily by observations (such as precipitation and radiation), the often severe atmospheric numerical weather prediction land surface forcing biases can be avoided. Secondly, by employing innovative land surface data assimilation techniques, observations of land surface storages (soil temperature, soil moisture, and snow depth/cover) can be used to constrain unrealistic simulated storages. Land data assimilation schemes also have the ability to maximize the utility of limited land surface observations by propagating their information throughout the land system to unmeasured times and locations.

We therefore propose to develop a, high-resolution, near-real-time Global Land Data Assimilation Scheme (GLDAS) using relevant remotely-sensed and in-situ observations within a land data assimilation framework. This development will greatly increase our skill in land surface, weather, and climate prediction, as well as provide high-quality, global land surface *assimilated data fields* that are useful for subsequent research and applications. Analysis of the constant confrontation of model predictions with observations at various time and space scales will provide an opportunity to improve our understanding and assessment of the space-time structure of land-atmosphere interaction, the relationship between model estimates and observations of land surface conditions, and the role of the land surface in regulating *seasonal-to-interannual* hydrologic and climatic variability.

Relevance

This proposal is submitted in response to the NASA Modeling Data and Analysis Research announcement (NRA-99-OES-04) and is directly relevant to the EOS Interdisciplinary Science Program (EOS/IDS). It is also highly relevant to the GEXEX, CLIVAR, PACS, ISLSCP, GSWP, and USGCRP programs among others. GLDAS integrates a wide variety of observational and modeling initiatives, and formally links the NOAA and NASA land surface research programs. GLDAS is the next logical step in NASA's ongoing efforts to understand the Earth's land-surface and to extend NASA's emerging observations for application to a vast array of socially-relevant land-surface issues.

Prior Accomplishments

The investigators have been actively working on various aspects of the land surface observation and simulation problem, so the proposed study will be enhanced by their past research results, as well as ongoing research activities. We specifically point to the ongoing continental-scale LDAS project described at http://ldas.gsfc.nasa.gov, that this proposed research will use as a baseline. The research proposed here enables the application of new powerful land surface observation, modeling, and data assimilation techniques to be applied to the critical and socially-relevant problem of practically predicting hydrologic and climatic phenomenon in near-real time.

Proposed Work and Methodology

We propose to develop a 1/8 degree resolution, near real-time Global Land Data Assimilation Scheme (GLDAS), using relevant observations with the following components: **(1)** *Land Modeling:* It is recognized that the results of GLDAS will be biased by its underlying modeling system. Therefore, the GLDAS driver will be developed in a modular fashion to facilitate the use of multiple commonly available land surface models. A runoff routing scheme will be implemented in the driver to facilitate runoff validation and the possible assimilation of lake/wetland/large river heights. (**2)** *Land Surface Observation*: We expect to use NCEP operational global meteorological predictions as the backbone of GLDAS forcing; however, to avoid known biases in these fields, we will replace them with observations wherever available. The additional use of observations constrain the GLDAS states using data assimilation methods emphasizes the importance of land observation in the proposed project. We will explore the use of all relevant, globally available land surface observations in the context of this project. (**3)** *Land Surface Data Assimilation*: Data Assimilation techniques merge a range of diverse data fields with a model prediction to provide that model with the best estimate of the current state of the natural environment so that it can then make more accurate predictions. We plan to develop a largely one-dimensional Kalman filtering based land assimilation strategy for use in GLDAS. (**4**) *GLDAS Calibration and Validation*: Since a number of land model states will be assimilated from observational data sets, the structure of the initialization scheme ensures their accurate reproduction. However, we will also compare to independent data sets, either *in-situ* or remote, as appropriate. Through the validation process, the quality of the land initialization will be evaluated, and if necessary, appropriate changes to the model structure, forcing, or parameters will be instituted to increase the reliability of its initialization.

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Technical Proposal

1. Problem Statement

Accurate assessment of the spatial and temporal variation of global land surface conditions are essential for addressing a wide variety of highly socially-relevant science, education, application, and management issues. Rainfall-runoff prediction, meteorologic processes studies, climate system and ecosystem modeling, and soil system science would all greatly benefit from improved knowledge of land surface conditions across the globe. Improved land surface state estimates would also find direct application in agriculture, forest ecology, civil engineering, water resources management, and crop system modeling. Additionally, as people increasingly modify the land surface, concern grows about the ensuing consequences for weather, climate, water supplies, crop production, biochemical cycles, and ecological balances of the biosphere at various time scales [Wetzel and Woodward, 1987]. These consequences are all strongly determined by human-induced changes in the land surface.

Most critically, accurate initialization of land surface moisture and energy stores in fully-coupled climate system models is critical for seasonal-to-interannual climatological and hydrological prediction because of their regulation of surface water and energy fluxes between the surface and atmosphere over a variety of time scales [Shukla and Mintz, 1982; Dirmeyer, 1997]. Subsurface moisture and temperature stores exhibit persistence on seasonal-to-interannual time scales; together with external forcing and internal land surface dynamics, this persistence has important implications for the extended prediction of climatic and hydrologic extremes [Namias, 1959; Delworth and Manabe, 1988, 1989; Dirmeyer and Shukla, 1993, Koster and Suarez, 1995; Beljaars *et al.* 1996]. It is also important to properly initialize snow; the presence of snow significantly modifies surface-atmosphere interaction through modification of surface albedo and melt processes, which often has a long-term anomalous persistence.

Because soil moisture, temperature, and snow are integrated states, errors in land surface forcing and parameterization accumulate in these stores, which leads to incorrect surface water and energy partitioning. However, through the NASA-EOS program, among others, many innovative new high-resolution land surface observations are becoming available that will provide the additional information necessary to constrain land surface predictions at global scales. These constraints can be imposed in two ways. Firstly, by forcing the land surface primarily by observations (such as precipitation and radiation), the often severe atmospheric numerical weather prediction land surface forcing biases can be avoided. Secondly, by employing innovative land surface data assimilation techniques, observations of land surface storages such as soil temperature and moisture can be used to constrain unrealistic simulated storages. Land data assimilation schemes also have the ability to maximize the utility of limited land surface observations by propagating their information throughout the land system to unmeasured times and locations.

Therefore, we propose to develop a 1/8 degree resolution, near real-time Global Land Data Assimilation Scheme (GLDAS), as a NASA-NOAA collaboration. This project is the logical extension of the current Land Data Assimilation Schemes (LDAS) multi-institution project that has developed a 1/8 North-American operational land-surface modeling and analysis system (Figure 1). We anticipate that the development of GLDAS will greatly increase land surface, weather, and climate predictive skill, as well as provide high-quality land surface assimilated data fields that are useful for subsequent research and applications. Additionally, it

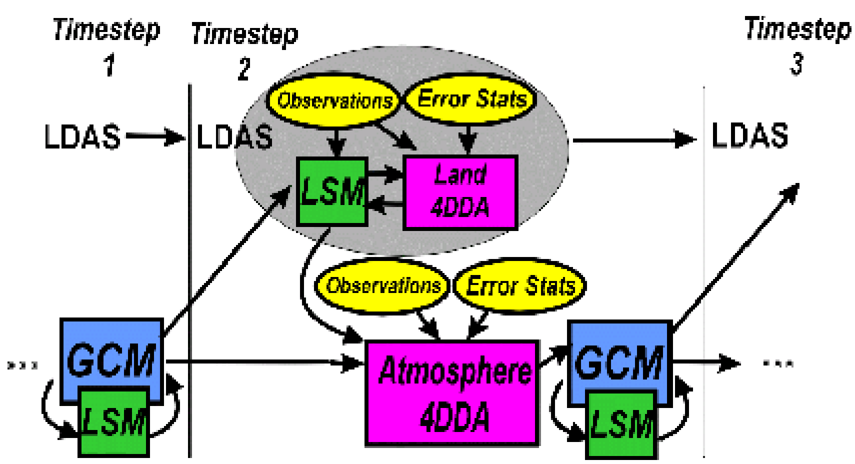


Figure 1: Interaction of the *Land Data Assimilation Scheme* (LDAS) with an operational *Numerical Weather Prediction* (NWP) system. The atmospheric *General Circulation Model* (GCM) is coupled with the *Land Surface Model* (LSM), and both use a *4-Dimensional Data Assimilation* (4DDA) process to integrate past forecasts with observations to improve performance.

will provide an improved understanding of the hydrological processes that control and are affected by climatic variability on a wide range of timescales.

Significant progress has been made in land-surface observation and modeling at a wide range of scales. Projects such as the International Satellite Land Surface Climatology Project (ISLSCP), the Global Soil Wetness Project (GSWP), and the GEWEX Continental-Scale International Project (GCIP), among others have paved the way for the development of an operational GLDAS. The development of GLDAS would serve as an integrating linkage between a variety of Earth science disciplines and geographical locations. But most importantly, GLDAS will integrate state-of-the-art modeling and observation on a operational basis to provide globally consistent high quality land states in a timely enough manner to be used in real-time applications.

2. Goals and Objectives

Our overarching hypothesis is that land surface simulation, observation, and analysis methods are sufficiently advanced to accurately determine global land-surface energy and moisture stores for the initialization of prediction systems and to address land-surface management issues. Therefore, to evaluate this hypothesis we will produce an operational 1/8 degree Global Land Data Assimilation Scheme that will integrate state-of-the-art land-atmospheric simulation with *in-situ* and remotely-sensed land surface observations using innovative land-surface data assimilation strategies. The resulting GLDAS fields will be evaluated for their accuracy and applicability in long-term hydrologic and climate prediction. Specific near-term objectives of this proposed research are as follows:

- Explore the sensitivity of global off-line land-surface simulations to variations in observed forcing, initial states, and surface characteristics. Sensitivity studies will focus on variables and model states that provide memory to the climate system at seasonal-to-interannual time scales (e.g. snow, soil moisture, total water storage, temperature, and runoff) and that are available globally from remote-sensing systems. This will provide insight into variables to which land model simulations are most sensitive, and would therefore warrant inclusion in a data assimilation scheme, more accurate description by remote observation, or both, in order to produce a set of realistic land model states.
- Develop a Kalman-filtering-based land assimilation strategy that builds upon previous work in two [Milly, 1986; Entekhabi *et al.*, 1994] and four [Houser *et al.*, 1998; Walker *et al.*, 1999] dimensions, and which utilizes remotely-sensed observations to force and constrain off-line land-surface simulations. The focus here will be to arrive at a increasingly realistic set of land surface states.
- Explore the sensitivity of coupled simulations to the improved initialization of the land surface at a wide variety of time scales, with implications for the role of land surface processes in the fully-coupled climate system. Use the results of previous objectives, to understand individually and collectively, the roles of those variables whose initialization has been improved by the research described in this proposal (e.g. snow areal extent, soil moisture, lake/wetland storage, temperature).

While the utilization of *in-situ* data in assimilation strategies, including their optimal blending with remote observations, is an important aspect of any data assimilation scheme, the focus of this work is on incorporating satellite data into our global land data assimilation framework. The globally sparse nature of relevant land observations, and the inconsistency of point measurements with model grid scales, poses technical and theoretical issues that are beyond the scope of the proposed work. We do however, intend to use *in-situ* observations for validation exercises at local and regional scales.

3. Programmatic Relevance

The proposed research is consistent with the EOS Interdisciplinary Science Program (EOS/IDS) goals of furthering the understanding of Earth System processes on global scales through modeling and data analysis techniques that make extensive use of remotely sensed data. GLDAS will directly investigate the interdependence of the global land surface and climate, and will include interdisciplinary investigations of surface biogeochemical processes. More broadly, the proposed research will address linkages between the global water and energy cycle, climate variability and prediction, and the biophysical processes which are three of the major scientific topics covered by NASA's Earth Science Enterprise (ESE). The proposed research is further relevant to the NASA-ESE science goals of developing methods to use satellite remote-sensing to improve the assessment and prediction of land surface hazards such as floods, droughts, etc., and assessing the impact of land cover and use on the Earth system. This research is also relevant to a variety of international research programs, through its provision of critical land surface data sets of interest to CLIVAR, GOALS, and GEWEX.

Furthermore, the proposed research is distinct, yet complementary to the land surface data assimilation activities currently being undertaken by NASA's Data Assimilation Office (DAO), and NASA's Seasonal-to-Interanual Prediction Project (NSIPP) at Goddard Space Flight Center (GSFC). Since the DAO is most interested in obtaining high quality, instantaneous atmospheric profiles of moisture and temperature for use by EOS instrument teams, its land surface data assimilation research is focused on surface soil skin temperature and atmospheric fluxes on short time scales and low resolutions. NSIPP requires retrospective high-quality estimates of land surface states with long-term memory that will improve long-term seasonal-to-interannual predictions. In distinct contrast, the focus of GLDAS is on obtaining very high-resolution realistic land surface conditions using state-of-the-art, newly emerging land-surface observation, simulation, and analysis technology in an operational context. The data assimilation methods, land observations, and validation required in this proposed research is distinct from activities underway at GSFC. However, there will be some common concerns in NSIPP and DAO land surface endeavors that will be aided through the close collaboration enabled through this research.

4. Background

Remote Sensing of the Land Surface: The emphasis of the proposed research will be to assimilate those remotely-sensed observations of the land surface that previous research suggests will provide memory to land-atmosphere interaction. Remote observations of interest include temperature, soil moisture (surface moisture content, surface saturation, total water storage), other surface water bodies (lakes, wetlands, large rivers) and snow (areal extent, snow water equivalent). The status of each of these is described in more detail below.

Remote sensing of surface temperature is a relatively mature technology. The land surface emits thermal infrared radiation at an intensity directly related to its emissivity and temperature. The absorption of this radiation by atmospheric constituents is smallest in the 3 to 5 and 8 to 14 :m wavelength ranges, making them the best windows for sensing land surface temperature. Some errors due to atmospheric absorption and improperly specified surface emissivity are possible, and the presence of clouds can obscure the signal. Generally, surface temperature remote sensing can be considered an operational technology, with many spaceborne sensors making regular observations (i.e. Landsat TM, AVHRR, MODIS, and ASTER) [Lillesand and Kiefer, 1994]. The evolution of land surface temperature is linked to all other land surface processes through physical relationships. We will exploit these land surface process interconnections in a data assimilation framework to use the observed evolution of surface temperature to correct all of the predicted land surface states.

Remote-sensing of soil moisture content is a developing technology, although the theory and methods are well established [Eley, 1992]. Long-wave passive microwave remote-sensing is ideal for soil moisture remote-sensing, but there are technical challenges in correcting for the effects of vegetation and roughness. Soil moisture remote sensing has previously been limited to aircraft campaigns [e.g. Jackson, 1997a], or analysis of the Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave Imager (SSM/I) [Engman, 1995; Jackson, 1997b]. SSM/I has also been successfully employed to monitor surface saturation/inundation [Achutuni and Scofield, 1997; Basist and Grody, 1997]. The EOS-Advanced Microwave Sounding Unit (AMSR) instrument will provide additional C-band microwave observations that may be useful for soil moisture determination when it is launched in 2000. The TRMM-TMI, which is very similar to AMSR, is much better suited to soil moisture measurement (because of its 10 Mhz channels) than SSM/I, and is also currently available. All of these sensors have adequate spatial resolution for land surface applications, but have a very limited quantitative measurement capacity, especially over dense vegetation. However, Sipple *et al.*, [1994] demonstrated that it is possible to determine saturated areas through dense vegetation using SMMR, which can greatly aid land surface predictions. Because of the large error in remotely-sensed microwave observations of soil moisture, there is a real need to maximize its information by using algorithms (such as the proposed methods) that can account for its error and that extend its information in time and space.

An important and emerging technology with respect to this project is the potential to monitor variations in total water storage (ground water, soil water, surface waters (lakes, wetlands, rivers), water stored in vegetation, snow and ice) using satellite observations of the time variable gravity field. The Gravity Recovery and Climate Experiment (GRACE), an Earth System Science Pathfinder mission, will provide highly accurate estimates of changes in terrestrial water storage in large watersheds when it is launched in 2001. Wahr *et al.* [1998] note that GRACE will provide estimates of variations in water storage to within 5 mm on a monthly basis. Rodell and Famiglietti [1998] have demonstrated the potential utility of these data for hydrologic applications, including their application in large (>150,000 km^2) watersheds; and they further discuss the potential power of GRACE for constraining modeled water storage in land surface models when combined with surface soil moisture and altimetery observations. Birkett [1995, 1998] demonstrated the potential of satellite radar altimeters to monitor height variations over inland waters, including climatically-sensitive lakes and large rivers and wetlands. Such altimeters are currently operational on the ERS-2 and TOPEX/POSEIDON satellites, and are planned for the ENVISAT and JASON-1 satellites.

Key snow variables of interest in this work include areal coverage and snow water equivalent. While the estimation of snow water equivalent by satellite is currently in research mode, snow areal extent can be routinely monitored by many operational platforms, including AVHRR, GOES and SSM/I. Recent algorithm developments even permit the determination of the fraction of snow cover within Landsat-TM pixels [Rosenthal and Dozier, 1996]. Cline *et al.* [1998], describe an approach to retrieve SWE from the joint use of remote sensing and energy balance modeling. The feasibility of implementing this approach on a global scale will be explored in the context of this research.

Modeling of the Land Surface: Recent advances in understanding soil-water dynamics, plant physiology, micrometeorology, and the hydrology that control biosphere-atmosphere interactions have spurred the development of Land Surface Models (LSMs), whose aim is to represent simply yet realistically the transfer of mass, energy, and momentum between a vegetated surface and the atmosphere [Dickinson *et al.*, 1993; Sellers *et al.*, 1986]. LSM predictions are regular in time and space, but these predictions are influenced by model structure, errors in input variables and model parameters, and inadequate treatment of sub-grid scale spatial variability. Consequently, LSM predictions of land surface hydrology and land surface states will likely be much improved by the assimilation strategy described in this proposal.

Three recent LSMs warrant further discussion with respect to this project. These are the Mosaic LSM of Koster and Suarez [1992] and Koster *et al.* [1998], the **N**ational Centers for Environmental Prediction (NCEP), **O**regon State University (OSU), United States **A**ir Force (USAF), and Office of **H**ydrology (OH), LSM, called **NOAH**, and the recently emerging Common Land Model (CLM).

The Mosaic LSM addresses the problem of subgrid heterogeneity by subdividing each GCM grid cell into a user-specified mosaic of tiles [after Avissar and Pielke, 1989], each tile having its own vegetation type and hence water and energy balance. Surface flux calculations for each tile are similar to those described by Sellers *et al.* [1986]. Tiles do not directly interact with each other, but influence each other indirectly, by their collective influence on the overlying atmosphere. Like the plethora of LSMs that have been developed over the past decade (e.g. the PILPS participants, Henderson-Sellers *et al.* [1993]), Mosaic is well suited to modeling the vertical exchange of mass, energy and momentum with the overlying atmosphere, but includes a poor representation of lateral moisture movement, which significantly controls variations in soil water, surface energy fluxes and runoff. Recognizing this weakness, Koster *et al.* [1998] developed a new, catchment-based LSM that includes a more realistic representation of hydrological processes, including the lateral transport of soil water through the subsurface. The catchment-based model, which relies heavily on the concepts originally put forth by Famiglietti and Wood [1991] and Famiglietti and Wood [1994] (i.e. the TOPLATS model), will represent a major advance in LSMs for the following two reasons. First, the TOPMODEL [Beven and Kirkby, 1979], topographically-based framework will result in improved runoff prediction, and consequently, more realistic catchment-scale water balance. Second, the downslope movement of moisture within the watershed will yield sub-catchment-scale variations of surface and unsaturated-zone moisture content, which will result in more realistic prediction of within-catchment variations in surface fluxes. Improved simulation of runoff will ultimately result in a more realistic flux of continental streamflow from the land to the oceans in the CGCM, and similarly, the within-catchment variations in surface fluxes result in more representative catchment-average exchanges with the atmosphere.

The NOAA-NOAH LSM simulates soil moisture (both liquid and frozen), soil temperature, skin temperature, snowpack water equivalent, snowpack density, canopy water content, and the traditional energy flux and water flux terms of the surface energy balance and surface water balance. This model has been used in a) the NCEP-OH submission to the PILPS-2d tests for the Valdai, Russia site, b) the emerging, realtime, U.S.-domain, Land Data Assimilation System (LDAS), c) the coupled NCEP mesoscale Eta model [Chen *et al*, 1997] and the Eta model's companion 4-D Data Assimilation System (EDAS), as well as in d) the coupled NCEP global Medium-Range Forecast model (MRF) and its companion 4-D Global Data Assimilation System (GDAS).

The Common Land Model (CLM) is being developed by a *grass-roots* collaboration of scientists who have an interest in making a general land model available for public use. By *grass roots*, we mean that the project is not being controlled by any single organization or scientist, but rather, the scientific steering is judged by the community. However, the project began at a sub-group meeting at the 1998 NCAR CSM meeting, and there is a plan to implement the CLM into the NCAR CSM by early 2000. The CLM development philosophy is that only proven and well-tested physical parameterizations and numerical schemes shall be used. The current version of the CLM includes superior components from each of three contributing models: LSM (G. Bonan, NCAR), BATS (R. Dickinson) and IAP (Y.-J. Dai). The CLM code management will be similar to *open source*, in that, use of the model implies that any scientific gain will be included in future versions of the model. Also, the land model has been run for a suite of test cases including many of the PILPS (Project for the Intercomparison of Land Parameterization Schemes) case studies. These include FIFE (Kansas, USA), Cabauw (Netherlands), Valdai (Russia), HAPEX (France), and the Amazon (ARME and ABRACOS). These cases have not been rigorously compared with observations, but will be thoroughly evaluated in the framework of the Project for the Intercomparison of Land-surface Parameterization Schemes (PILPS).

Justification for using an uncoupled LSM: There are strong justifications for studying an LSM uncoupled from atmospheric and ocean models, as is proposed for GLDAS. While, coupling the LSM to an atmospheric model allows for the study of the interaction and feedbacks between the atmosphere and land surface. However, coupled modeling also imposes strong land surface forcing biases predicted by the atmospheric model on the LSM. These biases in precipitation and radiation can overwhelm the behavior of LSM physics. In fact, several NWP centers must 'correctively nudge' their LSM soil moisture toward climatological values to eliminate its drift. By using an uncoupled LSM, we can better specify land surface forcing using observations, use less computational resources, and address virtually all of the relevant scientific questions. The physical understanding and modeling insights gained from implementing distributed, uncoupled land-surface schemes with observation-based forcing has been vividly demonstrated in recent GEWEX retrospective off-line land surface modeling projects known as PILPS-2c and the Global Soil Wetness Project [Koster and Milly, 1997].

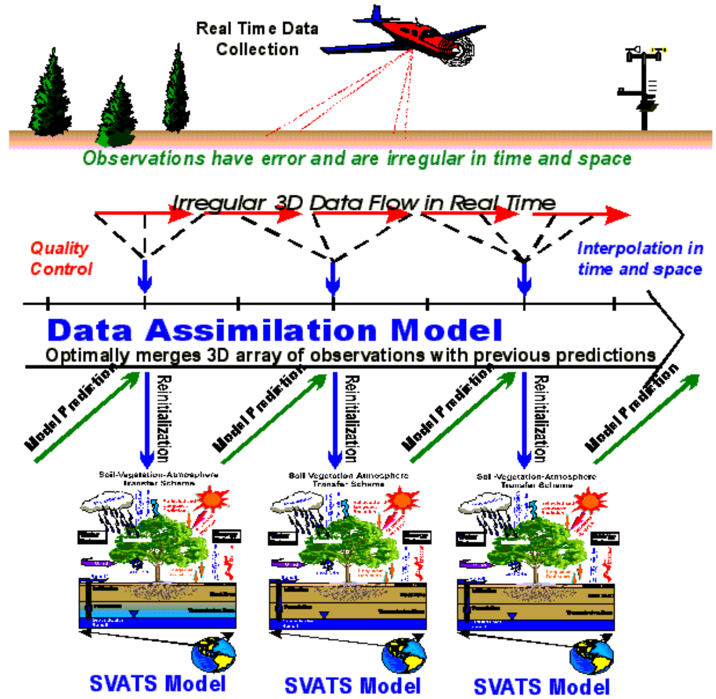


Figure 2: The land-surface data assimilation process.

Land Surface Data Assimilation: Charney *et al.* [1969] first suggested combining current and past data in an explicit dynamical model, using the model's prognostic equations to provide time continuity and dynamic coupling amongst the fields. This concept has evolved into a family of techniques known as *four-dimensional data assimilation* (4DDA). "Assimilation is the process of finding the model representation which is most consistent with the observations" [Lorenc, 1995]. In essence, data assimilation merges a range of diverse data fields with a model prediction to provide that model with the best estimate of the current state of the natural environment so that it can then make more accurate predictions (See Figure 2). The application of data assimilation in hydrology has been limited to a few one-dimensional, largely theoretical studies [i.e. Entekhabi *et al.*, 1994; Milly, 1986] primarily due to the lack of sufficient spatially-distributed hydrologic observations [McLaughlin, 1995]. However, the feasibility of synthesizing distributed fields of soil moisture by the novel application of 4DDA applied in a hydrological model was demonstrated by Houser *et al.* [1998]. Six Push Broom Microwave Radiometer (PBMR) images gathered over the USDA-ARS Walnut Gulch Experimental Watershed in southeast Arizona were assimilated into the TOPLATS hydrological model using several alternative assimilation procedures. Modification of traditional assimilation methods was required to use these high density PBMR observations. The images were found to contain horizontal correlations with length scales of several tens of kilometers, thus allowing information to be advected beyond the area of the image. Information on surface soil moisture was also assimilated into the subsurface using knowledge of the surface-subsurface correlation. Newtonian nudging assimilation procedures were found to be preferable to other techniques because they nearly preserve the observed patterns within the sampled region, but also yield plausible patterns in unmeasured regions, and allow information to be advected in time.

Land Data Assimilation Schemes (LDAS): The characterization of the spatial and temporal variability of water and energy cycles is critical for the improvement of our understanding of land surface-atmosphere interaction and the impact of land surface processes on climate extremes. Because accurate knowledge of these processes and of their variability is important for climate predictions, most NWP centers have incorporated land surface schemes into their models. However, errors in the NWP forcing accumulate in the surface and energy stores, leading to incorrect surface water and energy partitioning and adversely affecting related processes. This has motivated the NWP centers to impose ad hoc corrections to the land surface states to prevent this drift. *Land Data Assimilation Schemes* (LDAS), which are uncoupled land surface schemes that are forced primarily by observations, and are therefore not affected by NWP forcing biases are currently under development [Brutsaert *et al.*, 1998]. This research is being implemented in near

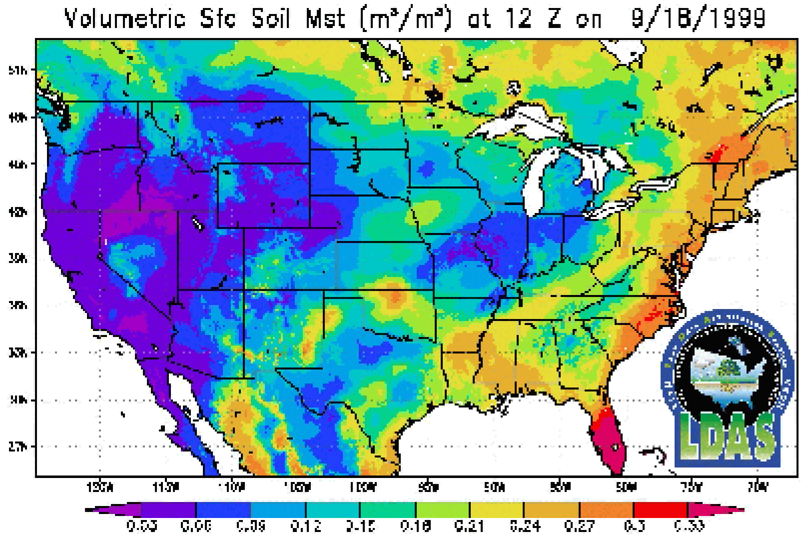


Figure 3: A near-real time LDAS soil moisture field.

real time using existing LSMs by NCEP, NASA, Princeton University, and the University of Washington at a 1/8th° (about 10 kilometer) resolution across the United States to evaluate these critical science questions. The LDAS are forced with real time output from numerical prediction models, satellite data, and radar precipitation measurements. Model parameters are derived from the high-resolution EROS vegetation coverages.

A real-time LDAS system is currently in place (please see http://ldas.gsfc.nasa.gov), that uses near-real time NCEP Eta model analysis fields, along with observed precipitation and radiation fields to force several different land surface models in an uncoupled mode (see Figure 3). Forcing, parameter, resolution, and prediction specifications for this North-American LDAS were carefully chosen by the inter-institution LDAS working group. We plan to build the Global LDAS as much as possible on these LDAS specifications, as will be described in the project work plan.

Global Soil Wetness Project (GSWP): Recognizing the importance of soil moisture in the climate system, the International Satellite Land Surface Climatology Project (ISLSCP), which is a contributing project of GEWEX, began the Global Soil Wetness Project (GSWP) in 1994. The initial efforts of the GSWP were to implement a land surface modeling effort using a CD-ROM set (Sellers et al., 1995; Meeson et al., 1995), developed by ISLSCP. The CDs contain, in addition to other information, meteorological observations and parameter data sets sufficient to obtain soil moisture estimates for 1987-1988 for a 1 X 1 degree grid. Ten groups, using various LSMs, including BATS, Mosaic, multiple versions of SiB, and others, produced soil moisture fields for these two years. Through the GSWP, Entin *et al.* [1999] attempted to validate these soil moisture fields using various soil moisture observations from the Northern Hemisphere mid-latitudes. They found that none of the models were able to recreate the actual soil moisture for all the areas studied. They did find that most of the models were able to recreate the seasonal cycle of soil moisture in Illinois and Russia, though all the models were deficient in recreating the changes of soil moisture in Mongolia and China. Some of the problems noted were the reliability of the forcing data set used as well as the consistency of the parameters for all the LSMs involved. A second CD-ROM set is planned by ISLSCP, which will contain data for at least ten years (1985-1994). The GSWP will use this data to force LSMs which should address another of the main issues raised when citing the difficulty of performing soil moisture validation.

Contrary to the GSWP, every scientist involved with GLDAS will be exposed to the entire process, from selecting the LSMs to finding the necessary parameters (vegetation, soil, etc.) for these models to creating a set of meteorological variables sufficient to force the LSMs. Although this will limit the number of scientists involved, we hope this will illuminate the connection between LSM performance and the data sets and decisions made to run the LSM and allow for more general contributions to the field of land-surface modeling than were possible with the GSWP.

5. Detailed Work Plan

Optimal operational (real-time) high-resolution global land surface data assimilation requires: (a) multiple high quality land surface process models capable of being atmospherically coupled; (b) observations of land-surface forcings, storages, and fluxes for constraining and validating the land surface initialization; and (c) an appropriate initialization strategy and data assimilation methodology to constrain the land surface process model with observations of surface forcings and storages. We will outline our proposed contributions to NASA EOS/IDS by first describing our global land surface data assimilation philosophy and approach, and then detailing the specifics of the approach.

Global Land Data Assimilation Philosophy and Approach: We have given a great deal of thought to our GLDAS strategy to determine how its various components will fit together for optimum land initialization. Our proposed GLDAS land surface assimilation strategy is summarized in Figure 1. In this strategy, the forcing for an off-line land surface model is given by the Numerical Weather Prediction (NWP) and observation systems that "spin-up" the land states to real-time. The land model provides a background "first guess" of its water and energy storages, which are merged with observations of land storages in the land data assimilation process. The land model is then reinitialized with the merged states.

The fully coupled prediction system is reinitialized with the off-line land surface model data assimilation states periodically. If this is done retrospectively, then the off-line data assimilation land surface states and observations can be used as validation and calibration of land surface initializations and coupled predictions.

GLDAS Working Group: In collaboration with NASA-ESE, and the land-surface modeling community, we propose the organization of a GLDAS land working group with the goals of encouraging complementary ideas and collaboration from a larger research group and developing potential GLDAS applications. This group will be comprised of 5 to 8 researchers, and potential end users that could help to maximize the practical development and use of our proposed research. Annual meetings, and regular email or conference call discussions will help to refine both the research proposed here, and GLDAS land research in general. Travel resources for this group have been included in the proposed budget.

Global Land Model Development and Implementation: Data assimilation requires a high-quality background prediction, so the chosen land surface prediction model must be physically realistic, able to capture diurnal land surface dynamics, and compatible with available remotely sensed and NWP forcing. The chosen model will be adapted for use on the 1/8th degree global grid and with available forcing, and modifications necessary for data assimilation will be made. It is recognized that the results of GLDAS will be biased by its underlying modeling system. Therefore, the GLDAS driver will be developed in a modular fashion to facilitate the use of multiple commonly available land surface models. Following the PILPS experience, we will implement several different models to evaluate their suitability.

A variety of land surface process models are appropriate for use in this study, but the Mosaic [Koster and Suarez, 1996], NOAH, and CLM land surface models will be the first to be used in GLDAS. The globe will be divided into approximately 4.1 million 1/8 degree model units, of which about 1/3 will be land. The LSMs will be implemented on an hourly cycle, for available forcing period.

Global Land Parameterization: A key step in the development of GLDAS will be the specification of model parameters for each 1/8th degree grid location. These vegetation and soil parameters vary spatially, and seasonally which complicate their specification. A great deal of effort has been given to this issue in the North-American LDAS project, which will serve as a starting point for parameterization of GLDAS. GLDAS vegetation will be largely defined by the 1km AVHRR classifications derived by the EROS data center and the University of Maryland (DeFries *et al.*, 1998). Further seasonal modification of these parameters will be made by applying satellite-derived greenness or leaf area index derived from AVHRR or MODIS. Finally, 1km global soil classifications are available from International Geosphere-Biosphere Program (IGBP) , and will be explored

Global Land Surface Forcing: Successful data assimilation requires a reasonably high quality, generally unbiased, land surface model prediction. The use of high quality global atmospheric forcing of the land surface is essential to produce reasonable land surface predictions. This is with out a doubt the most daunting and important part of creating a GLDAS. The global off-line land surface model requires wind speed, air temperature, humidity, precipitation, and radiation on a hourly basis. Many of these land surface forcing variables can be reliably provided by operational Numerical Weather Prediction (NWP) models (i.e. the NCEP GDAS) run in either a real-time or reanalysis mode. However, precipitation and radiation are generally poorly predicted by NWP models because we have not mastered the complex prediction of cloud physics and dynamics, which can lead to gross errors in land surface simulations. Therefore, we plan to replace these fields by some recently emerging observational products, when available. Unfortunately most high-quality long-term global land surface observations have been processed on monthly time scales for use in climate variability studies, and therefore lack the high temporal resolution required by land surface modeling efforts. These low temporal resolution observations can still be used to improve global land surface predictions by reducing the longer- term land surface forcing biases through a ratio correction. Essentially, we will use the NWP model forcing as high-resolution temporal weights on the longer-term observation averages when high-resolution observed forcing is unavailable. It is recognized that the timing of forcing is also of particular importance in land surface prediction, and therefore emerging temporal and spatial downscaling techniques will be explored to mitigate these effects.

Two general categories of satellite derived precipitation exist, each with severe limitations. However, it is generally acknowledged that they have less bias, and better location and timing of precipitation when compared to model estimates:

(1) GOES Precipitation Index (GPI) estimates from geostationary satellites [Arkin and Meisner, 1987]. This very simple method uses the cloud infrared brightness to directly estimate precipitation using a lookup table operation. This method can provide hourly precipitation estimates, but is limited to convective precipitation structures in the 40N to 40S longitude band. We will use the U.S. domain LDAS as a test bed to compare satellite estimates, GDAS, and the "ground truth" of the NCEP U.S. gage-only and radar/gage precipitation analyses.

(2) Shortwave passive microwave, as available with the SSM/I instrument, TRMM (Tropical Rainfall Measurement Mission), and AMSR (Advanced Microwave Scanning Radiometer) are sensitive to cloud water vapor quantities and raindrops, and can therefore provide superior estimates of precipitation. Because these satellites are not geostationary, their temporal coverage is limited. Many research groups have investigated the derivation of precipitation from this data using methods ranging from simple empirical systems to neural network techniques.

The quality of precipitation estimates is expected to be highest from microwave sensors, moderate from GPI, and lowest from the CGCM, and will therefore be used in that hierarchy or optimally merged following Houser *et al.* [1999]. Additional corrections for each data type based on gage and climatological information are expected to further benefit the accuracy of observed precipitation. Correction tables based on the differences between gage and satellite derived or GEOS-GCM precipitation differences will allow bias correction in future observations or more predictions.

Global downward shortwave radiation fluxes are also available [Pinker and Laszlo, 1992] using a surface solar irradiance model. This is a theoretical-spectral model and has shown success in producing the global surface solar radiation flux using ISCCP C1 data as input [Whitlock *et al.*, 1993], and has been extended to use ISCCP D1 data. The comparison between the ground-measured and estimated surface solar radiance over limited regions show that the mean root-mean-square errors are about 10-20 W/m^2 on daily time scales, and within 10 W/m^2 on a monthly time scale [Pinker and Laslo, 1992]. Gupta developed a parameterization for longwave surface radiation [Gupta, 1989] using satellite measurements. Recently, he improved and modified the algorithm [Gupta *et al.*, 1992] for direct use of ISCCP D1 data. In this algorithm, clear-sky downward flux was represented as a function of surface and lower tropospheric temperatures and water vapor burden of the atmosphere. Cloud contribution to the downward flux was represented in terms of cloud base temperature and water vapor burden of the atmosphere below the cloud. Additional near real-time radiation observations may be available from the NESDIS hourly 0.5 degree GOES-based surface solar insolation analysis.

Retrospective GLDAS: The majority of the focus for GLDAS will be on real-time operational implementation. However, we must not overlook the huge benefit of retrospective model analysis in understanding long-term system behavior, and for initialization studies. Therefore, there will be a modest retrospective component in GLDAS, largely based on the ISLSCP-2 initiative. The International Satellite Land Surface Climatology Project (ISLSCP) Initiative 2 data sets will build on the extremely successful ISLSCP Initiative 1 data sets by extending to 10+ years of global ½ degree 6 hour forcing based largely on observations. This will be a nearly ideal data set to study GLDAS in a retrospective mode. We will therefore closely collaborate with the development of the ISLSCP-2 data sets, and with the global Soil Wetness Project (GSWP) in the model evaluation of it.

Global Land Surface Observation: We will seek to develop and utilize remotely-sensed observations of land-surface states that are known to provide long-term memory to the land-atmosphere system at various time scales. These include snow (areal coverage), soil moisture (surface moisture content, total water storage, surface saturation), height of surface water bodies (lakes, wetlands, large rivers) and soil temperature. These will be used to constrain land system initialization for optimal predictive capacity. We will explore the utility of both long-term historical observations, and new land observations that will be available from EOS sensors, SMOS, GRACE, and radar altimetery. Currently, only routine observations of surface temperature and snow cover are available operationally over the globe. Hence, our initial efforts will focus on the use of these variables in GLDAS. Several operational sensors make regular observations of surface temperature. These include (or will include) Landsat TM, AVHRR, MODIS, ASTER and GOES. Areal coverage of snow is provided by AVHRR, GOES and SSM/I. We will investigate the usefulness of these observations in constraining the global land surface in a systematic fashion.

Remote sensing of at least two relevant soil water variables is anticipated in the near future. The GRACE mission will provide highly accurate estimates of variations in continental water storage, and will be launched within the time period of the proposed research (2001). Several groups are actively characterizing the spatial and

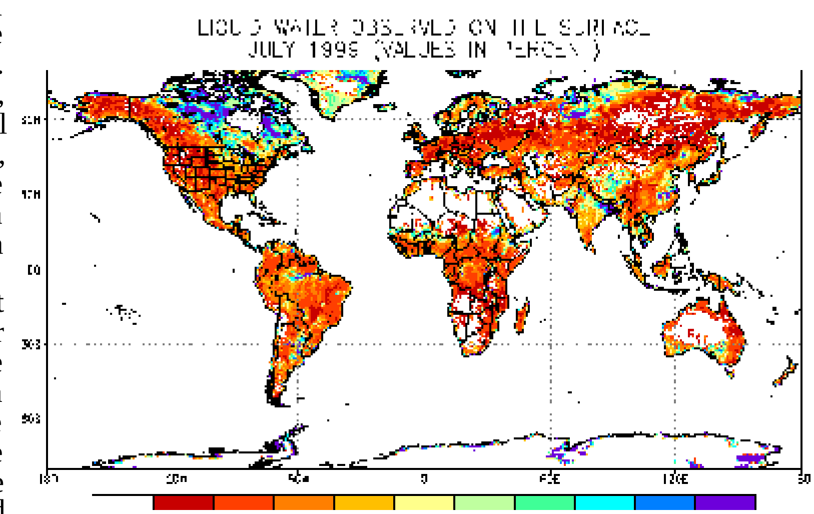


Figure 4: Liquid water observed on the surface by SSM/I.

temporal accuracy of GRACE-derived estimates of variations in total water storage, including error estimates. As part of the proposed research, we will explore how these estimates can be incorporated into the catchment-based model to constrain model predictions of total water storage; and how they can be used in conjunction with other data (e.g. snow cover and surface soil water) to disaggregate estimates of total water storage into water storage in soils versus storage in snow, etc. Surface soil moisture (0-2 cm) will be obtained from the C-band EOS AMSR sensor, and it may be provided by SSM/I, and ultimately by the European SMOS (0-5 cm). The investigators have significant experience in assimilating surface moisture content into various models. Further, surface saturation, can be derived from SSM/I [Basist and Grody, 1997], see Figure 4.

Radar altimetery will be used to constrain the level of inland surface water bodies, including lakes, wetlands and large rivers. Although these water bodies are not explicitly included in most land models, they are parameterized in the runoff routing model that will be implemented in GLDAS. Altimeters are currently on board TOPEX/POSEIDON, ERS-2, and are planned for ENVISAT and JASON-1.

Major tasks in this research will be the obtaining and processing (when necessary) the relevant products discussed above; matching those products with the model structure; modifying the model structure as appropriate (discussed in model development, above) and exploring the sensitivity of off-line LSM simulations to the input of each product on an individual basis. After demonstrating off-line sensitivity, we intend to further explore the sensitivity of coupled model simulations to individual variables (if possible), before constructing time series of each particular product and proceed with its implementation into the assimilation scheme.

***Global Land Surface Data Assimilation*:** Development of a four-dimensional data assimilation scheme to update modeled land surface states using all relevant remotely-sensed land surface observations is a primary focus of the proposed research.Land surface data assimilation is a promising, but not yet fully mature tool for constraining land-surface predictions. A great deal of research is currently underway at GSFC, NCEP, and several other institutions to develop land surface data assimilation methods. We will therefore work in close collaboration with these efforts to implement the best land-surface assimilation strategies. We plan to use a largely one-dimensional Kalman filtering based land assimilation strategy that expands upon the one-dimensional, largely theoretical assimilation algorithms developed Entekhabi *et al.*, [1994] and Milly, [1986], and the four-dimensional data assimilation strategies developed by Houser *et al.* [1998]. A two-dimensional assimilation scheme is appropriate for use in GLDAS because land surface states typically have short horizontal correlation distances, and remotely-sensed land-surface observations tend to have relatively high spatial resolution. However, because many land observations (such as runoff) are horizontally integrated values, or may cover multiple catchments or tiles, we may need to extend the proposed one-dimensional (in space) Kalman filter to four-dimensions.

Data Assimilation techniques merge a range of diverse data fields with a model prediction to provide that model with the best estimate of the current state of the natural environment so that it can then make more accurate predictions. The land data assimilation scheme will include the following steps:

(1) An error checking procedure will be established to correct or eliminate erroneous data [Bengtsson, 1985]. This is necessary because incorrect data can have a detrimental effect on the analysis, and can significantly reduce the quality of the predicted fields. Observations can contain different types of error, including errors due to faulty instruments, improper processing, or unsatisfactory communication of the data. Experience in previous land surface data assimilation efforts [Houser *et al*., 1998] suggests that we will require multiple levels of data checking.

(2) Observations can rarely be assumed to be physically and spatially identical to the modeled state. Therefore, in this research, an observation operator will be employed to facilitate bias correction, interpolation, and range matching.

(3) The analysis, or merging of observations with model predictions takes place in observation space based on the error characteristics of the model predictions and the observations using a Kalman filter data assimilation method. This process will produce the analysis increments or corrections that are used to force the model back toward the real state.

(4) In the proposed study, instead of adding the entire analysis increment in one time step, the analysis increments will be distributed in time around an observation to minimize discontinuities in predicted time series, as is done in Newtonian nudging or IAU (Incremental Analysis Unit) assimilation.

The proposed research will build on the soil moisture data assimilation strategies developed by Houser *et al.* [1998], Entekhabi *et al.* [1994], and Milly [1986]. This data assimilation scheme will attempt to obtain an optimal estimate of a land surface state by combining observations of that state with an LSM forecast of that state using a Kalman filtering approach. The Kalman filter has been extensively utilized in data assimilation research [Ghil *et al.*, 1981; Cohn, 1982]. The Kalman filter assimilation scheme is a linearized statistical approach that provides a statistically optimal update of the system states, bsed on the relative magnitudes of the covariances of both the model system state estimate and the observations. The principle advantage of this approach is that the Kalman filter provides a framework within which the entire system is modified, with covariances representing the reliability of the observations and model prediction. The Kalman filter [Kalman, 1960] tracks the conditional mean of a statistically optimal estimate of a state vector **X**, through a series of forecasting and update steps. To apply the Kalman filter, the equations for evolving the system states must be written in the linear state space formulation of (1). When these equations are non-linear, the Kalman filter is called the extended Kalman filter, and is an approximation of the non-linear system that is based on first-order linearization. The forecasting equations are [Bras and Rodriguez, 1985]:

$$\hat{X}^{n+1/n} = A^n \cdot \hat{X}^{n/n} + U^n + w^n \tag{1}$$

$$\Sigma_x^{n+1/n} = A^n \Sigma_x^{n/n} \cdot A^{n^T} + Q^n \tag{2}$$

where **A** is the state propagation matrix relating the system states at times *n+1* and *n*, **U** is a vector of forcing, **w** is model error, Σ_x is the covariance matrix of the system states and **Q** is the covariance matrix of the system noise (model error) defined as $E[\mathbf{w} \cdot \mathbf{w}^T]$. The notation *n+1/n* refers to the system state estimate at time *n+1* from a forecasting step, and *n/n* refers to the system state estimate from either a forecasting or updating step at time *n*.

The covariance evolution equation consists of two parts: (1) propagation by model dynamics and (2) forcing by model error. For the update step, the observation vector **Z** must be linearly related to the system state vector **X** through the matrix **H**:

$$Z = H \cdot \hat{X} + v \tag{3}$$

where **v** accounts for observation and linearization errors. The system state vector and covariances are updated by means of Bayesian statistics:

$$\hat{X}^{n+1/n+1} = \hat{X}^{n+1/n} + K^{n+1}\left(Z^{n+1} - H^{n+1} \cdot \hat{X}^{n+1/n}\right) \tag{4}$$

$$\Sigma_x^{n+1/n+1} = \left(I - K^{n+1} \cdot H^{n+1}\right) \Sigma_x^{n+1/n} \cdot \left(I - K^{n+1} \cdot H^{n+1}\right)^T + K^{n+1} \cdot R^{n+1} \cdot K^{n+1^T} \tag{5}$$

where **I** is the identity matrix. The Kalman gain matrix $\mathbf{K}^{n+1}$ weights the observations against the model forecast; it is determined by the relative magnitudes of model uncertainty, given by $\Sigma_x^{n+1/n}$ with respect to the observation covariances $\mathbf{R}^{n+1}$, defined as $E[\mathbf{v} \cdot \mathbf{v}^T]$. The Kalman gain is given by:

$$K^{n+1} = \Sigma_x^{n+1/n} \cdot H^{n+1^T} \cdot \left(R^{n+1} + H^{n+1} \cdot \Sigma_x^{n+1/n} \cdot H^{n+1^T}\right)^{-1} \tag{6}$$

The Kalman filter assumes that the continuous time error process w is a Gaussian white noise stochastic process with a mean vector equal to zero and parameter matrix **Q**, and that the discrete-time error sequence **v** is a Gaussian independent sequence with mean zero and variance **R**. The initial state vector $\hat{\mathbf{X}}^{0/0}$ is also assumed Gaussian with mean $\hat{\mathbf{X}}^{0/0}$ and the covariance matrix $\Sigma_x^{0/0}$. Given the initial state vector and covariance matrix, the system states and covariances are forecast using (1) and (2). When observations are available, an update to the system states and covariances is made using (4) and (5).

Observation Operator: We expect the temporal and spatial observations and predictions of land surface states to be roughly comparable. However, differences in measurement and model depths, observation noise, and model parameter and structure simplifications may require the model prediction and the remotely-sensed observation to be interpreted differently; the modeled and observed quantity may not have identical dynamic ranges and sensitivity [e.g. see Koster and Milly, 1997]. In fact, due to simplified LSM physics, the land surface states required to reproduce the correct fluxes may not be the same as the observed states. Eventually, we hope that (perhaps through this research) LSM will be refined so as to have both realistic states and realistic fluxes. Meanwhile, a method to 'translate' between land surface observations and predictions is required because all data assimilation methods assume that both the forecast and the observation are unbiased. An observation operator can be used to perform the needed translation between prediction space and observation space. In this case, the observation operator will convert and interpolate modeled states into observation space using well established theory. Then, the differences in the ranges and possibly the nonlinear relationship between the predicted and observed states will be accounted for before assimilation into the model. This will prevent gross model or observation bias from degrading model performance when observations are assimilated.

Model and Observation Error Covariance: The model error covariance structures needed in the data assimilation algorithm will be derived from extensive spatial and temporal error analysis of the observations, land model predictions, and land model physics. Since the number of observations at any given time is much less than the number of degrees of freedom in the model, it is not possible to estimate all the required parameters for specifying the required error covariance structures. This necessitates the use of a parameterized error covariance model to reduce the problem's degrees of freedom. Once a suitable model is chosen, parameters can be found using a gradient minimization approach.

Land-Surface Ensemble Prediction: An interesting aspect of GLDAS is the possibility of multiple land-surface predictions made by several different LSMs, with various initializations. These various land surface prediction ensembles will be intercompared and explored. It is quite possible that through this land-surface ensemble prediction strategy, spatially-varying confidence limits on predictions could be established and new ways to evaluate and improve predictions could be developed.

Runoff Routing: As part of GLDAS, a runoff-routing scheme will be implemented, which will allow model validation and assimilation using ground-based and remote streamflow observations. [Lohmann, *et al.*, 1996]. Further, Famiglietti *et al.* [1998] and Olivera *et al.* [1998] describe the development of river transport methods for the NCAR CSM that can be coupled to the GLDAS. Since current plans for the routing model include a parameterization of lakes and wetlands, coupling the catchment LSM with the river transport scheme will also allow for assimilation of altimetery-derived water heights.

Scaling studies: The land surface interacts with the atmosphere very differently depending on the scale it is modeled. It is well established that sub-grid variability can profoundly impact land-surface predictability. Therefore, the dependance of land surface predictions moisture predictions on spatial resolution and parameter aggregration will be assessed with a multi-scale sensitivity experiment. We will test the GLDAS performance over a range of scales, from 1km to 2 degrees. Parameters and forcing will be transferred between scales using standard aggregation algorithms, along with simple interpolation. These scaling studies will help to identify (1) the sensitivity of GLDAS predictions to spatial resolution, (2) mechanisms for relating and transferring results between scales, and (3) the importance of sub-grid scale heterogeneity on land-surface storage estimation.

Validation Strategy: Since a number of land model states will be assimilated from observational data sets, the structure of the assimilation scheme ensures their accurate reproduction. However, we will also compare to independent data sets, either *in-situ* or remote, as appropriate. The following data sets will be considered for use in this component of the study.

(a) Regionally-averaged *in-situ* validation: Various *in-situ* land observations are available for direct validation of land surface predictions (e.g. FIFE, BOREAS, SGP97, CASES, MAGS, GCIP). Because of the different times at which the smaller experiments were conducted, they may only provide insights into, for example, the magnitude of the surface fluxes to be expected during the time of year when the experiments were conducted. Conversely, large experiments like GCIP and MAGS have sponsored focused efforts to archive existing data, and may prove to be an important source of validation information for our work.

(b) Streamflow validation: A stream flow routing algorithm [e.g. Lohmann *et al*., 1996] will be incorporated in the GLDAS to facilitate validation of predicted states and fluxes via runoff.

(c) Surface temperature validation: Simulated surface temperature is dependent on model forcing, land surface characteristics, soil water storage, and internal model physics. So, surface temperature can provide an integrated assessment of land surface predictive quality. Since high quality land surface temperature observations are available from AVHRR [Dubayah *et al*., 1997], and will be available from EOS and will be valuable for GLDAS validation.

(d) Snow extent and water equivalent validation: Snow cover information derived from AVHRR, GOES, and SSM/I is available from various operational centers [Robinson *et al*., 1993], and can be useful for evaluating the snow accumulation and melt processes of the GLDAS. Further, validation data for model predictions of snow water equivalent are compiled by the National Weather Service National Operational Hydrologic Remote Sensing Center, and include *in-situ* snow course measurements and airborne snow water equivalent measurements which are compiled in gridded map format for the U.S. and Canada.

(e) Long-term budget partitioning validation: Over long time periods, the GLDAS should estimate the partitioning of available surface energy into sensible, latent, and ground heat fluxes, and the partitioning of precipitation into evaporation, runoff, and groundwater recharge correctly. Relatively reliable estimates of this partitioning have been established for various sub-regions and watersheds, and will be a valuable check on GLDAS performance.

(F) LDAS-GLDAS cross-validation: Due to its access to hourly gage and NEXRAD radar precipitation observations, the current continental-scale LDAS project will have forcing and prediction states that can be intercompared with GLDAS.

Through the validation process, the quality of the GLDAS prediction will be evaluated, and if necessary, appropriate changes to the GLDAS structure, forcing, or parameters will be instituted to increase the reliability of its predictions.

Dynamic GLDAS Coupled Model Initialization: A series of fully-coupled NCEP GDAS simulations will be performed using GLDAS land-surface initialization to determine the prediction sensitivity on the initial land state over a variety of timescales, and to optimize our algorithms for determining this state. These fully-coupled predictions will be performed in close collaboration with our NCEP investigators. We will explore the impact of the land surface initialization by comparing fully-coupled predictions from runs made with and without the initialization; and with standard climatology indices such as global precipitation (GPCP), temperature fields, and streamflow observations. Results the proposed sensitivity studies will provide insight into the mechanisms by which the newly initialized variables interact with the atmosphere, alone or in synergism, to impact the overall climate simulations.

An important additional source of validation data will also be provided by running the land assimilation scheme forward, in uncoupled mode, beginning from the same initial state that was provided to the coupled model. Offline model states will be compared to land model states in the coupled model, with implications for coupled model accuracy and for climate interactions that may lead to discrepancies between the uncoupled and coupled simulations.

***Public Interfaces and Outreach*:** Earth science researchers and practitioners are increasingly inundated with land-surface observations and model output in disparate formats and locations. Land-surface observations have a great potential to benefit society, but often are overlooked due to a lack of access, interest, or expertise. Therefore, to enable and inspire land surface research, education, and applications using a wide range of observations and model analyses using our GLDAS products, we propose the development of interactive web-based data analysis tools based on the latest World Wide Web, hardware, and land-surface analysis and modeling technologies that would be linked via a public interface to real-time GLDAS observations and land model analyses. It will enable scientists, students, and managers to interactively access, analyze, compare, understand, and validate information derived from GLDAS.

This public interface will support a wide variety of research, education, and applications. For example, a farmer could simply pull up a set of real-time soil moisture observations and operational model predictions to determine if the conditions are suitable for planting. Or, more complex, a river forecaster could determine which combination of land models, forcings, and observations would have produced the most accurate prediction of a previous flood (and therefore improve future performance). High school students could download the latest GLDAS imagery and model analysis for their region and compare them to their school's weather station. A NASA engineer could evaluate current sensor performance and relevance to modern usage to improve the design of future instruments. It will enable a wide range of land-surface research and applications The proposed system will be designed to enable students and scientists to learn about NASA observation resources and research, and to bring these resources to the public.

"NASA is deeply committed to spreading the unique knowledge that flows from its aeronautics and space research...."(from http://www.nasa.gov)**.** Our proposed public interface very clearly facilitates this primary NASA goal, and has significant potential to contribute to NASA science, information technology, and education. This proposed research is also directly relevant to NASA's Earth Science Enterprise by advancing our understanding and observation of the Earth system.

GLDAS Future Prospects: We have proposed the development of an operational 1/8 degree Global Land Data Assimilation Scheme. With the successful implementation of GLDAS will come the desire to continue its development to include increasingly useful modeling strategies and observations, to extend it for use in real-world applications, as well as maintaining its day-to-day implementation. The research proposed here enables the application of new powerful land surface observation, modeling, and data assimilation techniques to be applied to the critical and socially-relevant problem of practically predicting hydrologic and climatic phenomenon in near-real time. GLDAS integrates a wide variety of observational and modeling initiatives, and formally links the NOAA and NASA land surface research programs. GLDAS is the next logical step in NASA's ongoing efforts to understand the Earth's land-surface and to extend NASA's emerging observations for application to an array of socially-relevant land-surface issues.

6. Management Approach, Deliverables, Schedule, and Metrics

The proposed work will be conducted in close collaboration between NASA's Goddard Space Flight Center (GSFC) and NOAA's National Centers for Environmental Prediction (NCEP), and will draw much support from interdisciplinary community collaboration. The GLDAS team will consist of seven well-qualified scientists with complementary expertise, two full-time research assistants, a variety of student interns, and a rather wide scope of collaborators. Dr. Paul Houser (0.25 MY) will be responsible for overall project direction and coordination, and will provide scientific input for land surface simulation and data assimilation strategies. Dr. Michael Bosilovich (0.1 MY) will contribute to CLM development, validations of the annual and diurnal surface state and predictions, the interannual variability, and surface vegetation specifications. Dr. H. L. Pan (0.1 MY) will coordinate the transfer of NCEP operational global analysis and forecast fields, supervise the work of the research associate in the testing of the GLDAS soil moisture impact, and organize the NCEP diagnosis effort on the forecast impact. Dr. K. Mitchell (0.1 MY) will facilitate the derivation of GLDAS forcing [downward solar and longwave radiation using satellite-derived cloud cover, precipitation (comparing satellite-dominated precipitation estimates with independent gage/radar analyses), and terrain height adjustments in going from 4DDA-based forcing at one spatial resolution to a different GLDAS resolution], atmospheric predictability impact studies [mainly impacts on temperature and precipitation], at 5-500 km grid-spacing scales and daily to 365-day temporal scales, not only with NCEP/EMC GCMs, but also with NCEP imbedded higher resolution regional models, such as the Eta model, ensemble streamflow prediction, and satellite-based vegetation character and snowcover. Dr. Jeffrey Walker (0.1 MY) will implement Kalman filter techniques for GLDAS, and will act as a liaison to the NASA Seasonal-to-Interannual Prediction Project (NSIPP). Mr. Brian Cosgrove (0.1 MY) will oversee web tool development and provide scientific input for data usage. Dr. Jared Entin (0.1 MY) will oversee the acquisition and processing of observations, and the development of interactive land-surface modeling.

A collaborative working relationship has been established with other researchers working on *Land Data Assimilation Schemes* (LDAS). Dr. E. Wood (Princeton), Dr. D. Lettenmaier (Univ. of Washington), and

Dr. J. Schaake (NWS Office of Hydrology) will collaborate on the development of a runoff routing scheme to update and validate the GLDAS, and we will collaborate on the general development, implementation, and validation of the GLDAS. These collaborations will be partially facilitated by a 1-year visit of Princeton postdoc to GSFC and NCEP (funded independently by an existing NOAA-GCIP project). We will also collaborate with Dr. Randy Koster at GSFC on upgrades to LSM modeled processes.

We expect to deliver an operational pilot GLDAS, accessible on a public web interface within one year of embarking on this project. However, we fully expect to continue the development and support of GLDAS past this pilot phase to assure that it enhances the NASA Earth Science Enterprise into the future.

Experience shows us that there must be clarity if there is to be the proper completion of the task. We have clearly outlined the GLDAS task above, and we feel that while ambitious, it will provide a significant contribution to NASA's expertise within the time frame of this project. SEI (Software Engineering Institute) software engineering and management tools will be employed to assure high-quality GLDAS software development. This includes regular internal formal technical reviews to evaluate the developing GLDAS against the requirements outlined above, to formally introduce new GLDAS ideas, and to derive metrics of GLDAS success. Furthermore, we will adhere to ISO9001 requirements that are based on common sense project management and well known principles of quality science.

Project Tasks

1. Algorithm Development
- 1.1 Identify, evaluate, and dynamically acquire land forcing from NWP and observations.
- 1.2 Identify and implement global LSM parameter specifications.
- 1.3 Develop and implement multi-LSM GLDAS driver.
- 1.4 Develop data assimilation land surface algorithm.
- 1.5 Global runoff routing development.
- 1.6 Develop land ensemble prediction strategy.
- 1.7 Develop and implement public GLDAS web access tools.

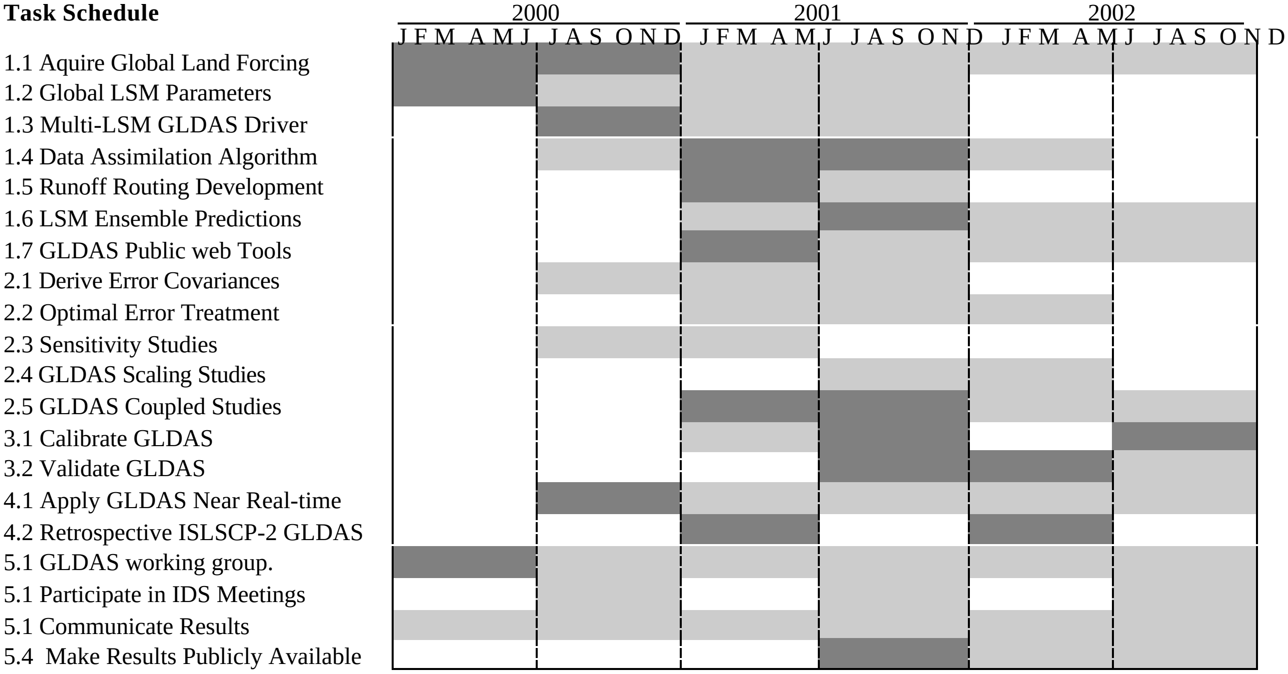
2. Investigate
- 2.1 Derive covariance error structures from analysis of spatial land surface observation fields.
- 2.2 Determine optimal treatment of model and data error.
- 2.3 Perform various sensitivity studies.
- 2.4 Investigate GLDAS scaling and sub-grid variability.
- 2.5 Investigate impact of GLDAS reinitialization of coupled predictability.

3. Evaluate
- 3.1 Calibrate and optimize the GLDAS land data assimilation scheme.
- 3.2 Evaluate and validate off-line and coupled predictions.

4. Extend
- 4.1 Apply the fully developed GLDAS in global near-real time applications.
- 4.2 Participate in ISLSCP-2 retrospective GLDAS studies.

5. Communicate
- 5.1 Form and involve GLDAS land working group.
- 5.2 Participate in IDS team meetings and conferences.
- 5.3 Communicate results and recommendations to the scientific community.
- 5.4 Make results publicly available for use in applications.

Task Schedule



Degree of shading denotes activity on each sub-task

7. Supporting Facilities and Equipment

NASA-GSFC and NOAA-NCEP maintain a formidable variety of technical expertise and computational resources (Silicon Graphics, Sun, and Hewlett Packard workstations, and Cray super-computers) in support of scientific analysis and for front-end and post-processing work. However, the proposed research involves the manipulation of large data sets and execution of large models which requires sufficient computational and storage resources. So, the purchase of additional computer hardware for this project is proposed.

Resource Request and Justification

All the investigators will receive a percentage of their support for their contribution to this project, except Houser, Mitchell, and Pan who as Civil Servants will donate their time to the project. Two research assistants (2.0 MY) shall be employed, one at NASA-GSFC, and one at NOAA-NCEP to support the development of GLDAS. In addition, several graduate students sponsored using separate GSFC funding will support this project. $10 K/year is allocated for travel to IDS and scientific conferences and to support the GLDAS working group. $5-8 K/year is required to support communication and publication costs. $2.5 K/year is allocated for general office supplies. $30 K is allocated for the acquisition of a devoted state-of-the-art GLDAS web-server and data-processing center, and for workstations for use by research assistants at both NCEP and NASA. Based on our experience with the LDAS, we expect that an Alpha processor-based server will meet the anticipated web-tool usage, database access, and real-time modeling requirements of GLADS. Further, based on the very large data sets required by GLADS, we anticipate the need for and additional $15 K of disk space in year 2. Finally, $5 K/year is required for computer system maintenance and security. NCEP will donate office space and LAN infrastructure for the NCEP research assistant. The proposed budget is summarized below.

Annual Budget:	***Year 1***	***Year 2***	***Year 3***	***3 Year Total***
1. Personnel				
PI (Houser): 0.25 MY (U.S. CS)				
Co-I (Mitchell): 0.1 MY (U.S. CS)				
Co-I (Pan): 0.1 MY (U.S. CS)				
Co-I (Bosilovich): 0.1 MY (USRA)	$9,130	$9,587	$10,066	$28,782
Co-I (Walker): 0.1 MY (USRA)	$7,870	$8,264	$8,677	$24,810
Co-I (Entin): 0.1 MY (Raytheon)	$8,130	$8,537	$8,963	$25,630
Co-I (Cosgrove): 0.1 MY (GSC)	$6,670	$7,004	$7,354	$21,027
Contractor: 1.0 MY (NASA)	$79,840	$83,832	$88,024	$251,696
Contractor 1.0 MY (NOAA)	$79,840	$83,832	$88,024	$251,696
2. Communication and publication				
Publication charges	$5,000	$5,000	$8,000	$18,000
Supplies	$2,500	$2,500	$2,500	$7,500
Travel	$10,000	$10,000	$10,000	$30,000
3. Hardware				
Computer Hardware	$30,000	$15,000	$0	$45,000
Computer Maintenance	$2,500	$2,500	$2,500	$7,500
4. NASA-GSFC assessments:				
Branch & Division assessments (6%)	$14,639	$14,313	$14,196	$43,148
GSFC Multiple Program Support:	$29,680	$32,993	$36,703	$99,375
Total GSFC Project Cost:	***$288,299***	***$285,860***	***$287,506***	***$861,664***

Return on Investment

GLDAS is a relatively straightforward and inexpensive way to greatly enhance the cohesion and usability of NASA's land surface science and observation expertise. The potential return on investment of GLDAS is large. GLDAS can help NASA scientists and engineers to understand the value of existing sensors, and help them to design increasingly superior instruments. GLDAS will greatly facilitate use of NASA data and products by scientists, students, and the public across the globe. For the first time, GLDAS will put research-quality land-surface modeling tools in the hands of educators who can use them to fuel the creativity of their students without bogging them down in the complexities of data format issues. Finally, it is quite possible that through GLDAS, NASA observations could improve the understanding of natural hazards (such as floods, droughts, and landslides), land use change and agriculture, and weather/climate prediction, all of which could have a large positive economic impact.

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BUDGET SUMMARY

NASA's Goddard Space Flight Center

Year 1

For Period from January 1, 2000 to December 31, 2000.

- Provide a complete Budget Summary for year 1 and a separate estimated for each subsequent year.
- Enter the proposed estimated costs in Column A (Columns B & C for NASA use only).
- Provide as attachments detailed computations of all estimates in each cost category with narratives as required to fully explain each proposed cost. See *Instructions For Budget Summary* on following page for details.

		NASA USE ONLY	
	A	**B**	**C**
1. Direct Labor (salaries, wages, and fringe benefits)	$191,480	________	________
2. Other Direct Costs			
a. Subcontracts	$0	________	________
b. Consultants	$0	________	________
c. Equipment	$30,000	________	________
d. Supplies	$2,500	________	________
e. Travel	$10,000	________	________
f. Other	$10,000	________	________
3. Facilities and Administrative Costs	$44,319	________	________
4. Other Applicable Costs:	$0	________	________
5. SUBTOTAL–Estimated Costs	$288,299	________	________
6. Less Proposed Cost Sharing (if any)	$0	________	________
7. Carryover Funds (if any)	$0		
a. Anticipated amount: $0.00	$0		
b. Amount used to reduce budget	$0	________	________
8. Total Estimated Costs:	$288,299	________	XXXXXXX
9. APPROVED BUDGET	XXXXXXX	XXXXXXX	________

BUDGET SUMMARY

NASA's Goddard Space Flight Center

Year 2

For Period from January 1, 2001 to December 31, 2001.

• Provide a complete Budget Summary for year 1 and a separate estimated for each subsequent year.
• Enter the proposed estimated costs in Column A (Columns B & C for NASA use only).
• Provide as attachments detailed computations of all estimates in each cost category with narratives as required to fully explain each proposed cost. See *Instructions For Budget Summary* on following page for details.

		NASA USE ONLY	
	A	**B**	**C**
1. Direct Labor (salaries, wages, and fringe benefits)	$201,054	________	________
2. Other Direct Costs			
a. Subcontracts	$0	________	________
b. Consultants	$0	________	________
c. Equipment	$15,000	________	________
d. Supplies	$2,500	________	________
e. Travel	$10,000	________	________
f. Other	$10,000	________	________
3. Facilities and Administrative Costs	$47,306	________	________
4. Other Applicable Costs:	$0	________	________
5. SUBTOTAL–Estimated Costs	$285,860	________	________
6. Less Proposed Cost Sharing (if any)	$0	________	________
7. Carryover Funds (if any)	$0		
a. Anticipated amount: $0.00	$0		
b. Amount used to reduce budget	$0	________	________
8. Total Estimated Costs:	$285,860	________	XXXXXXX
9. APPROVED BUDGET	XXXXXXX	XXXXXXX	________

BUDGET SUMMARY
NASA's Goddard Space Flight Center
Year 3

For Period from January 1, 2002 to December 31, 2002.

• Provide a complete Budget Summary for year 1 and a separate estimated for each subsequent year.
• Enter the proposed estimated costs in Column A (Columns B & C for NASA use only).
• Provide as attachments detailed computations of all estimates in each cost category with narratives as required to fully explain each proposed cost. See *Instructions For Budget Summary* on following page for details.

	A	NASA USE ONLY B	NASA USE ONLY C
1. Direct Labor (salaries, wages, and fringe benefits)	$211,107	________	________
2. Other Direct Costs			
a. Subcontracts	$0	________	________
b. Consultants	$0	________	________
c. Equipment	$0	________	________
d. Supplies	$2,500	________	________
e. Travel	$10,000	________	________
f. Other	$13,000	________	________
3. Facilities and Administrative Costs	$50,899	________	________
4. Other Applicable Costs:	$0	________	________
5. SUBTOTAL–Estimated Costs	$287,506	________	________
6. Less Proposed Cost Sharing (if any)	$0	________	________
7. Carryover Funds (if any)	$0		
a. Anticipated amount: $0.00	$0		
b. Amount used to reduce budget	$0	________	________
8. Total Estimated Costs:	$287,506	________	XXXXXXX
9. APPROVED BUDGET	XXXXXXX	XXXXXXX	________

A Global Land Data Assimilation Scheme (GLDAS)
Submitted to NRA-99-OES-04: *NASA-ESE Modeling and Data Analysis Research, EOS/IDS*

Paul R. Houser, Michael Bosilovich, Brian Cosgrove, Jared K. Entin, and Jeffrey Walker
NASA's Goddard Space Flight Center(GSFC), Hydrologic Sciences Branch; Greenbelt, MD 20771

Hua-Lu Pan and Kenneth Mitchell
NOAA's National Centers for Environmental Prediction(NCEP), Camp Springs, MD 20746

Current and Pending Support

1. Principle Investigator: ***Dr. Paul R. Houser***

Continental-Scale Soil Moisture Data Assimilation

The objective of this project is to develop a Land Data Assimilation Scheme (LDAS) for the continental U.S., and to test a hypothetical soil moisture data assimilation system. An LDAS is an uncoupled Land Surface Model that is primarily forced with observations to avoid systematic bias often associated with numerical weather prediction forcing. This project will assimilate synthetic observations of soil moisture.

Source: NRA97-MTPE12. *PI:* P. R. Houser (GSFC) *Co-I:* B. Choudhury
Award: $80 K /yr *Period:* FY 1998 - FY 2000

Remote Sensing Soil Moisture using Four Dimensional Data Assimilation of TRMM Microwave Observations

The primarily objective of this work is the development of an optimal methodology for extracting spatially and temporally continuous soil moisture fields from multi-frequency, multipolarization, TRMM passive microwave observations. This method will use the predictions of a land surface model that is primarily forced by observations, along with a microwave radiative transfer model to predict microwave brightness temperature (the forward problem). Then, in microwave observation space (i.e. brightness temperature), differences between observations and predictions will be analyzed. Finally, this analysis will be projected bask onto the model's soil moisture space to correct its trajectory using four dimensional data assimilation methods. This system will be implemented over the U.S. at a spatial resolution of 1/8 degree, for an extended period.

Source: NRA98-OES02 *PI:* P. R. Houser(GSFC) *Co-I's:* B. Choudhury (GSFC), J. Wang (GSFC)
Award: $110 K/yr *Period:* FY 1999 - FY 2001

Optimal Land Initialization for Seasonal Climate Predictions

The primary objective of this work is to explore the optimal initialization of the land system in NASA's Seasonal-to-Interannual Prediction Project (NSIPP) using relevant remotely-sensed observations within a land data assimilation framework. This strategy will merge the predictions of NSIPP's land surface model that is primarily forced by observations, with observations of those predictions using data assimilation methods. This work will focus on a 20 year global retrospective analysis using the catchment model developed by Koster and Suarez.

Source: NRA98-OES07. *PI's:* P. R. Houser (GSFC) and J. Famiglietti (U.of Texas)
Award: $200 K/yr *Period:* FY 1999 - FY 2001

Soil Moisture Data Assimilation for Continental-Scale Land Surface Hydrology Applications NRA-98-OES-11

The principal objective of this collaborative MIT-GSFC proposal is to provide an operational system for estimating soil moisture and temperature at the accuracy and resolution required for continental scale land surface hydrology applications. The extensive Southern Great Plains (SGP97) data set will be used to test the soil moisture data assimilation procedure developed in our proposed project. In particular, we will generate soil moisture and temperature estimates on a base-scale of 100 by 50 grid of 1 km by 1 km pixels in four or more vertical layers spanning the top 2 meters of the soil column. These estimates will be based on multi-sensor measurements (airborne L-band radiometer, surface precipitation radar, tower micrometeorology, soil and vegetation surveys). The capabilities of the system for estimation across scales (down-scaling) based on the resolution of data on forcing (e.g. micrometeorology) and parameters (e.g. soil and vegetation mapping) will also be tested.

Source: NRA98-OES11 *PI:* D. McLaughlin (MIT) Co-I's: D. Entekhabi (MIT), P. Houser (GSFC)
Award: $120 K/yr *Period:* FY 1999 - FY 2001

Quantifying the Relationship Between Remotely-Sensed and Modeled Soil Moisture NRA-98-OES-11

The primary objective of this work is to explore the optimal initialization of the land system in NASA's Seasonal-to-Interannual Prediction Project (NSIPP) using relevant remotely-sensed observations within a land data assimilation framework. This strategy will merge the predictions of NSIPP's land surface model that is primarily forced by observations, with observations of those predictions using data assimilation methods. This work will focus on a 20 year global retrospective analysis using the catchment model developed by Koster and Suarez.

Source: NRA98-OES11. *PI's:* C. Peters-Lidard (Georgia T.) *Co-I's:* P. O'Neill(GSFC), P. Houser (GSFC)
Award: $120 K/yr *Period:* FY 1999 - FY 2001

2. Co-Principle Investigator: ***Dr. Michael Bosilovich***
No current funded projects.

3. Co-Principle Investigator: ***Brian Cosgrove***
No current funded projects.

4. Co-Principle Investigator: ***Dr. Jared Entin***
No current funded projects.

5. Co-Principle Investigator: ***Dr. Kenneth Mitchell***

The NOAA Core Project for the Global Energy and Water Cycle Experiment (GEWEX) Continental-scale International Project (GCIP).

The objective of this project is to develop, test, refine, and intercompare land-surface process schemes in both a) stand-alone water resource applications and b) coupled atmospheric/land numerical weather prediction (NWP) models and their companion 4-D data assimilation systems, spanning a wide spectrum of spatial scales including 10-1000 km spatial scales and 1-365 day time scales. Coupled model experiments will focus on the relative role of land-surface processes in improving the predictability of the atmospheric energy and water cycle, including precipitation, PBL, and near-surface temperature, humidity, and winds.

Source: NOAA's Office of Global Programs (OGP), Climate and Global Change Program.
Co-PIs: John Schaake, Kenneth Mitchell, Dan Tarpley
Award: (to NCEP/EMC): $570 K / yr
Period: FY 1999 - FY 2001

6. Co-Principle Investigator: ***Dr. Hua-Lu Pan***
No current funded projects.

7. Co-Principle Investigator: ***Dr. Jeffrey Walker***
No current funded projects.

Paul R. Houser

March 21, 2000

Hydrological Sciences Branch & Data Assimilation Office
NASA's Goddard Space Flight Center

NASA-GSFC Code 974; Greenbelt, MD 20771
Tel: 301/614-5772 *Fax:* 301/614-5808

Email: Paul.Houser@gsfc.nasa.gov
Web: http://land.gsfc.nasa.gov

CAREER OBJECTIVE:

To perform environmentally significant scientific research and instruction in hydrology, near-surface meteorology, and remote sensing. Specific interests include local to global land surface-atmospheric observation (both in-situ and remotely-sensed) and numerical simulation, development of hydrologic data assimilation methods, and multi-scale soil moisture investigations.

EDUCATION:

Doctorate in Hydrology and Water Resources: *Remote-sensing Soil Moisture using Four-dimensional Data Assimilation,* College of Engineering and Mines, The University of Arizona; Tucson, AZ: November 1996.

Bachelor of Science in Hydrology and Water Resources: College of Engineering and Mines, The University of Arizona; Tucson, AZ: May 1992. Magna Cum Laude.

EXPERIENCE:

NASA Research Scientist: Goddard Space Flight Center, Greenbelt, MD: 4/97-present.
Data assimilation research that integrates hydrologic observations into land surface process models.

NASA Program Manager: NASA Headquarters, Washington DC: 9/99-3/00.
Management and planning of NASA's Land Surface Hydrology Program.

Post-Doctoral Research Scientist: Universities Space Research Association, Greenbelt, MD: 1/97-4/97.
Soil moisture remote sensing and data assimilation research.

Research Associate: University of Arizona, Tucson, AZ: 8/95-12/96. Developed data assimilation techniques for integrating remotely sensed soil moisture into hydrologic models.

Micrometeorological Site Development: University of Arizona; Tucson, AZ: 1/93-8/96.
Developed and operated an Eddy Correlation, Bowen Ratio, Sigma-T and Automatic Weather Station.

Teaching Assistant: University of Arizona, Hydrology Department; Tucson, AZ: 6/93,6/94,6/95.
Instructed undergraduate and graduate students in summer hydrology field camp.

Teaching Assistant: University of Arizona, Hydrology Department; Tucson, AZ: 1/93-5/95.
Instructed ~40 undergraduate students in Hydrology 250:"Principles of Hydrology".

Research Assistant: University of Arizona, Hydrology Department; Tucson, AZ: 5/92-9/92.
Characterized flow through fractures in volcanic tuff using air permeability techniques.

Laboratory Assistant: University of Arizona, Tree Ring Laboratory; Tucson, AZ: 1/92-4/92.
Measured and analyzed tree rings for paleoclimate reconstruction.

Research Assistant: Los Alamos National Laboratory, New Mexico, Environmental Sciences: Summer 1991. Emplaced field experiments to measure water balance relationships in various landfill scenarios.

Hydrologic Technician: U.S. Geological Survey, Water Resources Division; Portland, OR: 1988-90.
Used various field and laboratory techniques to assess the surface and ground water quality in the Yakima river basin, in south-central Washington State.

HONORS:

Goddard Space Flight Center Special Act Award, December 1997.
American Geophysical Union Hydrology Section Outstanding Student Paper, Spring 1996.
National Aeronautics and Space Administration Fellow in Global Change Research.
The National Science Foundation Graduate Fellowship.
Department of Energy Environmental Restoration and Waste Management Scholarship.

ACTIVITIES:

American Geophysical Union; Remote Sensing Committee.
American Meteorological Society.
The Institute of Electrical and Electronics Engineers, Inc.
International Association of Hydrological Sciences.

RECENT PUBLICATIONS:

Houser, P. R., D. C. Goodrich, and K. H. Syed, 1999: Runoff, Precipitation, and Soil Moisture at Walnut Gulch. In Spatial Patterns in Catchment Hydrology: Observations and Modeling, edited by R. Grayson and G. Bloschl.

Houser, P. R., 1999: Infiltration and Soil Moisture Processes. In Handbook of Weather, Climate, and Water, edited by T. Potter and B. Bradely.

Houser, P. R., H. V. Gupta, W. J. Shuttleworth, and J. S. Famiglietti, 1999: Multi-Objective Calibration and Sensitivity of a Distributed Land-Surface Water and Energy Balance Model. Under review.

Houser, P. R., and B. P. Mohanty, 1999. The spatial-temporal structure of U.S. Southern Great Plains soil moisture - an analysis of in-situ SGP97 profile observations. In the American Meteorological Society Proceedings of the 14th Conference on Hydrology, January 10-14, 1999.

Mohanty, B. P., P. R. Houser, P. J. Shouse, and M. Th. Van Genuchten, 1999. Soil moisture content at

deeper depths - SGP97, Oklahoma. In the American Meteorological Society Proceedings of the 14th Conference on Hydrology, January 10-14, 1999.
Bosilovich, M. G. P. R. Houser, A. Molod, and S. Nebuda, 1999. A comparison of FIFE observations with GEOS assimilated data including a heterogeneous land-surface model. In the American Meteorological Society Proceedings of the 14th Conference on Hydrology, January 10-14, 1999.
Famiglietti, J. S., J. A. Devereaux, C. A. Laymon, T. Tsegaye, P. R. Houser, T. J. Jackson, S. T. Grham, M. Rodell, and P. J. van Oevelen. Ground-based investigation of soil moisture variability within remote sensing footprints during the Southern Great Plains 1997 (SGP97) Hydrology Experiment. Water Resources Research, 35)6_:1839-1851.
Elliott, R. L., P. R. Houser, and B. K. Mohanty, 1999. Inter-comparison of three methods for measuring soil moisture during SGP97. In the American Meteorological Society Proceedings of the 14th Conference on Hydrology, January 10-14, 1999.
Houser, P. R., R. Yang, M. Bosilovich, A. Molod, and S. Nebuda, 1999. Spin-up time scales of the off-line land surface GEOS assimilation (OLGA) system. In the American Meteorological Society Proceedings of the 14th Conference on Hydrology, January 10-14, 1999.
Molod, A., S. Nebuda, M. Bosilovich, P. Houser, and R. Yang, 1999. The impact of the Mosaic land surface model on the climate of the GEOS data assimilation system. In the American Meteorological Society Proceedings of the 14th Conference on Hydrology, January 10-14, 1999.
Nebuda, S., A. Molod, M. Bosilovich, P. Houser, and R. Yang, 1999. Interaction of predicted and prescribed soil moisture with the moist physics parameterizations in the GEOS data assimilation system. In the American Meteorological Society Proceedings of the 14th Conference on Hydrology, January 10-14, 1999.
Yang, R., P. Houser, and J. Joiner, 1999. Comparizon of surface ground temperature from satellite observations and the off-line surface GEOS assimilation system. In the American Meteorological Society Proceedings of the 14th Conference on Hydrology, January 10-14, 1999.
Houser, P. R., C. Harlow, W. J. Shuttleworth, T. O. Keefer, W. E. Emmerich, and D. C. Goodrich, 1998: Evaluation of Multiple Flux Measurement Techniques Using Water Balance Information and a Semi-Arid Site. In: The American Meteorological Society Proceedings, February 12-16, 1998, Phoenix, AZ.
Houser, P. R., 1998: Microwave Soil Moisture Remote Sensing. Proceedings of the ECMWF/GEWEX MMP Workshop on Modeling and Data Assimilation for Land-Surface Processes, June 29 - July 2, 1998; ECMWF, Reading, UK
Houser, P. R., W. J. Shuttleworth, H. V. Gupta, J. S. Famiglietti, K. H. Syed, and D. C. Goodrich, 1998: Integration of Soil Moisture Remote Sensing and Hydrologic Modeling using Data Assimilation. *Water Resources Research,* **34**(12):3405-3420.
Houser, P. R.,J. S. Famiglietti, W. J. Shuttleworth, J. A. Berglund, 1997. Integration of Remote Sensing and Hydrologic Modeling Using Data Assimilation. In the American Meteorological Society Proceedings of the 13th Conference on Hydrology, February 2-7, 1997.
Houser, P. R., 1997: The Spatial-Temporal Structure of U.S. Southern Great Plains Soil Moisture: A Preliminary Analysis of SGP97 Observations. In the proceedings of the *Characterization and Measurement of the Hydraulic Properties of Unsaturated Porous Media International Workshop*.
Unland H., A. Arain, C. Harlow, P. Houser, H. Garatuza, R. Scott, O. Sen, and W. Shuttleworth, 1997: Evaporation from a Riparian System in a Semi-arid Environment. *Hydrol. Process.* **12**(1998):527-542.
White, C. B., P. R. Houser, A. M. Arain, Z. L. Yang, K. Syed, and W. J. Shuttleworth, 1997. The aggregate description of semi-arid vegetation with precipitation-generated soil moisture heterogeneity. *Hydrology and Earth Systems Sciences*, 1, 205-212.
Houser, P. R., 1996: Remote Sensing Soil Moisture using 4-Dimensional Data Assimilation. Ph.D. dissertation, Department of Hydrology and Water Resources, The University of Arizona.
Unland, H. E., P. R. Houser, W. J. Shuttleworth, and Zong L. Yang, 1996. Surface Flux Measurement and Modeling at a Semi-Arid Sonoran Desert Site, submitted to*: Journal of Agricultural and Forest Meteorology*, September 1, 1995; approved for publication.
Twine, T. E., W. P. Kustas, J. M. Norman, D. R. Cook, P. R. Houser, T. P. Meyers, J. H. Prueger, P. J. Starks, 1999: Underestimation of Eddy Covariance Fluxes over a grassland. Under review.
Yang R., S. Cohn, A. da Silva, J. Joiner, and P. Houser, 1999: Internal Physical Features of a Land Surface Model Employing a Tangent Linear Model. Submitted to *Monthly Weather Review*.

RESEARCH GRANTS:

Houser, P. R., and J. S. Famiglietti, 1999-2001: Optimal Land Initialization for Seasonal Climate Predictions, NASA NRA 98-OES-07, $600k.
Houser, P. R., J. R. Wang, and B. Choudhury, 1999-2001: Remote Sensing Soil Moisture using Four Dimensional Data Assimilation of TRMM Microwave Observations, NASA NRA 98-OES-02, $330k.
Houser, P. R., and B. Choudhury, 1998-2000: Continental-Scale Soil Moisture Data Assimilation, NASA NRA 97-MTPE-12, FY 1998-2000, $240k (see http://ldas.gsfc.nasa.gov).
Houser, P. R., H. Gupta, W. J. Shuttleworth, D. Goodrich, J. Famiglietti, and J. Berglund, 1994-1998: Remote Sensing Soil Moisture Using Four-Dimensional Data Assimilation, NASA Project NAGW-4165, NASA-MTPE Water Cycle Processes Program.
McLaughlin, D. (MIT), D. Entekhabi (MIT), and P. R. Houser, 1999-2001: Soil Moisture Data Assimilation for Continental-Scale Land Surface Hydrology Applications, NASA NRA-98-OES-11, $360k,
Christa Peters-Lidard (Georgia Tech), Paul R. Houser and Peggy E. O'Neill (NASA-GSFC), 1999-2001: Quantifying the Relationship Between Remotely-Sensed and Modeled Soil Moisture,NASA NRA-98-OES-11, $360k.

CURRICULUM VITAE: HUA-LU PAN

1. Vital Statistics

Born: 8 July 1947, Shanghai, China

Present Position: Chief, Global Modeling Branch
Environmental Modeling Center
NCEP/NWS
W/NMC23, WWB, Room 204
Washington, D. C. 20233

Home Address: 11000 Rutledge Drive
Gaithersburg, MD. 20878

2. Education

B.S. (1970) - Physics, Tsing Hua University, Taiwan

M.A. (1973) - Physics, Temple University

M.S. (1975) - Meteorology, Florida State University

Ph.D. (1979) - Meteorology, Florida State University

3. Professional Employment

1981-1987: Assistant Professor, Department of Atmospheric Sciences, Oregon State University, Corvallis, Oregon

1988-1998: Research Meteorologist, Environmental Modeling Center, National Centers for Environmental Prediction, Washington, D.C.

1998-present:Chief, Global Modeling Branch, Environmental Modeling Center, NCEP, NWS, Washington, D.C.

4. Professional Affiliation

Member, American Meteorological Society

5. Publications in Reviewed Literature

1976: Numerical simulation of Somali Jet. J. Atmos. Sci., 33, 2350-2362 (T.N. Krishnamurti, J. Molinari and H.-L. Pan)

1977: Downstream amplification and formation of monsoon disturbances. Mon. Wea. Rev., 105, 1280-1297 (T.N. Krishnamurti, J. Molinari, H.-L. Pan and V. Wong)

1977: Numerical weather prediction relevant to the monsoon problem. Pure and Appl. Geophys. 115, 1157-1372 (T.N. Krishnamurti, J. Molinari, H.-L. Pan, and V. Wong)

1979: Numerical Weather Prediction for GATE. Quart.J.Roy. Meteor. Soc., 105, 979-1010 (T.N. Krishnamurti, H.-L. Pan, C.B. Chang, J. Ploshay, D. Walker, and A.W. Oodally)

1980: Cumulus parameterization and rainfall rate. I., Mon. Wea. Rev., 108, 465-472 (T.N.

Krishnamurti, H.-L. Pan, R.J. Pasch, and J. Molinari)

1983: A three-dimensional planetary boundary layer model for the Somali jet. J. Atmos. Sci., 40, 894-908 (T.N. Krishnamurti, V. Wong, H.-L. Pan, R. Pasch, J. Molinari and P. Ardanny)

1983: Details of low latitude medium range numerical weather prediction using a global spectral model I: Formation of a monsoon depression. J. Meteor. Soc. Japan, 61, 188-207 (T.N. Krishnamurti, R.J. Pasch, H.-L. Pan, S.-H. Chu and K. Ingles)

1984: A two-layer model of soil hydrology. Boundary-Layer Meteor., 29, 1-20 (L. Mahrt and H.-L. Pan)

1985: The 10-20 day tropical-midlatitude interactions during the winter monsoon season. J. Meteor. Soc. Japan, 63, 829-844 (H.-L. Pan and F.-X. Zhou)

1987: Interaction between soil hydrology and boundary-layer development. Boundary-Layer Meteor., 38, 185-202 (H.-L. Pan and L. Mahrt)

1987: Wintertime 10-20 day variations in the upper troposphere. J. Meteor. Soc. Japan, 64, 932-940 (H.-L. Pan)

1990: A high resolution air mass transformation model for short-range weather forecasting. Mon. Wea. Rev., 118, 1561-1575 (A.A.M. Holtslag, E.I.F. De Bruijn and H.-L. Pan)

1990: A simple parameterization scheme of evapotranspiration over land for the NMC Medium-Range Forecast model. Mon. Wea. Rev., 118, 2500-2512 (H.-L. Pan)

1991: Recent changes implemented into the Global Forecast System at NMC. Wea. Forecasting, 6, 425-435 (M. Kanamitsu, J.C. Alpert, K.A. Campana, P.M. Caplan, D.G. Deaven, M. Idedell, B. Katz, H.-L. Pan, J. Sela and G.H. White)

1996: Comparison of NCEP-NCAR reanalysis with 1987 FIFE data. Mon. Wea. Rev., 124, 1480-1498 (A.K. Betts, S.-Y. Hong and H.-L. Pan)

1996: Nonlocal boundary layer vertical diffusion in a medium-range forecast model. Mon. Wea. Rev., 124, 2322-2339 (S.-Y. Hong and H.-L. Pan)

CURRICULUM VITA

Name: Kenneth E. Mitchell

Title: Meteorologist

Organization: National Centers for Environmental Prediction/National Weather Service

Career Objective: Improving numerical weather prediction (NWP) over a wide range of spatial and temporal scales spanning 5-500 km and daily to weekly and seasonal. Advancing the parameterization of diabatic energy and moisture processes in coupled land/atmosphere prediction and simulation models, including land-surface, boundary-layer, cloud microphysics, precipitation, radiation, and convection. Application of satellite-remote sensing to defining land-surface characteristics and states (e.g. snow cover, vegetation, soil moisture, skin temperature) in coupled land-atmosphere models.

Professional Address:

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5200 Auth Road
Camp Springs, MD 20746
Tel: 301-763-8000 (x 7225)
Fax: 301-763-8545
Email: Kenneth.Mitchell@noaa.gov
Web: http://www.ncep.noaa.gov

Home address:

1522 Farlow Ave
Crofton, MD 21114

Education:

Degree	Major Subject	Date	University
B.S.	Meteorology	1973	Pennsylvania State University
M.S.	Meteorology	1975	Pennsylvania State University
Ph.D.	Meteorology	1979	Pennsylvania State University

Professional Societies:

American Meteorological Society (1972-present)

Positions Held:

1973-1978: Graduate Research Assistant, Pennsylvania State Univ.
1978-1982: Advanced Weather Officer, U.S. Air Force (military)
1979-1981: Adjunct Professor, Physics Dept, Creighton University, Omaha, NE
1982-1988: Atmospheric Physicist, Air Force Geophysics Lab (Federal Civil Service)
1988-present: Research Meteorologist and Team Leader for Land/Hydrology Research
1998- present: Adjunct Professor, Dept of Atmospheric Sciences, Univ. of Oklahoma, Norman, Ok

Vital statistics: born 29 Jul 51 in Hinsdale IL.

Dr. Mitchell has been lead-author on two and co-author on 18 published refereed papers in scientific journals, and has had more than 55 non-refereed publications. He is serving as a member of two national/international scientific panels, and has presented papers at more than 70 workshops and scientific meetings.

Dr. Mitchell is married, has two children, and resides in Crofton, Maryland.

BRIAN ALLEN COSGROVE

General Sciences Corporation
Hydrological Sciences Branch and Data Assimilation Office
NASA Goddard Space Flight Center

NASA/GSFC Mail Code 974 Tel. 301-614-5803 Fax. 301-614-5808
Greenbelt, Maryland 20771 Email: Brian.Cosgrove@gsfc.nasa.gov

Research: Land Surface Modeling, Dynamic Vegetation Modeling, Data Assimilation, Lake Effect Snow Modeling, Design and Implementation of Web-Based Visualization Systems, General Web Design

Education: Master of Science, Meteorology, August 1998; The Pennsylvania State University, University Park, PA

Bachelor of Science with Honors, Atmospheric Sciences, May 1996; Cornell University, Ithaca, NY

Experience: General Sciences Corporation, NASA Goddard Space Flight Center, Greenbelt, MD *Atmospheric Scientist*, 9/98-Present

· Conducted data assimilation research utilizing the Mosaic Land Surface Model (LSM) as part of the Land Data Assimilation Schemes (LDAS) Project.

· Created a web-based Real-time Image Generator (RIG) for use on the LDAS web site. The RIG allows for interactive viewing of forcing data and model output data from the LSMs involved in the LDAS project.

The Pennsylvania State University, University Park, PA *Graduate Research Assist.*, 8/96-8/98

· Conducted multiple global climate simulations utilizing the GENESIS global climate model, and investigated vegetation-climate feedbacks.

· Created a simplified dynamic vegetation model and coupled it to the GENESIS GCM.

The Pennsylvania State University, University Park, PA *Research Assistant*, 5/96-8/96

· Conducted a series of soil science experiments to study the nature of moisture transport through several types of soil.

· Responsible for study design, procedural aspects, and execution of experiment.

Rutgers University, Piscataway, NJ *Undergraduate Assistant to the New Jersey State Climatologist*, 5/95-8/95

· Used the C programming language to develop a statistics-based ensemble of programs to verify the long-term accuracy of thermometer calibration at New Jersey State weather stations.

· Created and maintained internet web sites for the New Jersey State Climatologist.

Cornell University, Ithaca, NY *Teaching Assistant*, 8/94-12/94

· Created answer keys, graded papers and dealt with student questions for SCAS 231: Climate and Climate Change.

Honors: The Father James B. Macelwane Award in Meteorology, 3rd Place, AMS, 1996.
Graduate Scholar, The Pennsylvania State University, 1996.
The Local 1262 Union Scholarship for Academic Excellence, 1992, 1994.

Professional Affiliations: American Meteorological Society

Publications: Cosgrove, B. A., Houser, P. R. and Entin, J. K. (1999) A Real-time Land Data Assimilation Scheme. 16th International Conference on Interactive Information and Processing Systems (IIPS) for Meteorology, Oceanography, and Hydrology. Preprints. Submitted.

Cosgrove, B. A. (1998) A Simplified Dynamic Vegetation Model Coupled to the GENESIS GCM. Masters Thesis, Department of Meteorology, The Pennsylvania State University. PSUCLIM (co-author) (1997) The Sensitivity of Severe Storms to Climate Forcing Factors on Geologic Time Scales. *Journal of Geophysical Research*. Submitted.

PSUCLIM (co-author) (1997) Storm Activity in Ancient Climates: An Analysis Using Climate Simulations and Sedimentary Structures. *Journal of Geophysical Research*. Submitted.

Cosgrove, B. A. (1996) Lake Effect Snow in the Finger Lakes Region.15th Conference on Weather and Forecasting. Preprints, pages 573-576.

Presentations: Cosgrove, B. A., Houser, P. R. and Entin, J. K. A Real-time Land Data Assimilation Scheme. 16th International Conference on Interactive Information and Processing Systems (IIPS) for Meteorology, Oceanography, and Hydrology. 1999. Accepted.

Houser, P. R., Cosgrove, B. A. and Entin, J. K. Realtime Continental Scale Land Surface Modeling and Data Assimilation. GCIP Principal Investigators Meeting. College Park, Maryland. May, 1999.

Cosgrove, B. A. A Simplified Dynamic Vegetation Model for Use with the GENESIS GCM. Wengen-97 Workshop on Global Change. Wengen, Switzerland. September, 1997.

Cosgrove, B. A. Lake Effect Snow in the Finger Lakes Region. 15th Conference on Weather and Forecasting. Norfolk, Virginia. August, 1996.

MICHAEL G. BOSILOVICH

EDUCATION

May 1997 Purdue University West Lafayette, IN
Ph.D. - Atmospheric Science (Dept. of Earth and Atmospheric Science)
Dissertation: Numerical Simulation of the 1993 Midwestern Flood

December 1992 Purdue University West Lafayette, IN
MS - Atmospheric Science (Dept. of Earth and Atmospheric Science)
Thesis: A Parameterization for the Surface Boundary Layer: Formulation and Verification

May 1990 Millersville University Millersville, PA
BS-Meteorology

PROFESSIONAL EXPERIENCE

1997 - Present Universities Space Research Association Greenbelt, MD
Visiting Scientist

Conduct post-doctoral research in collaboration with NASA DAO scientists primarily validating the surface/atmosphere interactions in the GEOS Data Assimilation System (with Dr. S. Schubert)

1993 - 1997 Purdue University West Lafayette, IN
Research Assistant

Conduct research on modeling the land-surface and the interactions with precipitating systems

1990 - 1993 Purdue University West Lafayette, IN
Teaching Assistant

Taught upper level undergraduate meteorology lab courses (Atmospheric Dynamics and Synoptic Meteorology); included significant freedom to independently develop lectures, exercises and exams

PUBLICATIONS

Bosilovich, M. G. and W.-Y. Sun, 1999: Numerical Simulation of the 1993 Midwestern Flood: Local and Remote Sources of Water. J. Geophys. Res., D 104, 19415-19424.

Bosilovich, M. G., R. Yang and P. Houser, 1999: River basin hydrology in a global off-line land-surface model. J. Geophys. Res., D 104, 19661-19674.

Bosilovich, M. G. and W.-Y. Sun, 1999: Numerical Simulation of the 1993 Midwestern Flood: Land - Atmosphere Interactions. J. Climate, 12, 1490-1505.

Bosilovich, M. G. and S. D. Schubert, 1998: A comparison of GEOS assimilated data with FIFE observations. NASA Tech. Memorandum 104606, GSFC, Greenbelt, MD 20771.

Bosilovich, M. G. and W.-Y. Sun, 1998: Monthly simulation of surface layer fluxes and soil properties during FIFE. J. Atmos. Sci., 55, 1170 - 1184.

Sun, W.-Y., M. G. Bosilovich and J.-D. Chern, 1997: Regional response of the NCAR CCM1 to anomalous surface properties. TAO, 8, 271-288.

Sun, W.-Y. and M. G. Bosilovich, 1996: Planetary boundary layer and surface layer sensitivity to land surface parameters. Bound.-Layer Met., 77, 353-378.

Bosilovich, M. G. and W.-Y. Sun, 1995: Formulation and verification of a land surface parameterization for atmospheric numerical models. Bound.-Layer Met., 73, 321-341.

CONFERENCE PRESENTATIONS

Bosilovich, M. G., A. Molod, P. R. Houser, and S. D. Schubert, 1999: Validation of Mosaic heterogeneity in the GEOS DAS. 2nd WCRP Conference on Reanalyses, August 1999, Reading UK.

Bosilovich, M. G., S. D. Schubert, A. Molod and P. R. Houser, 1999: Validation of land-surface processes in the GEOS DAS. 2nd WCRP Conference on Reanalyses, August 1999, Reading UK.

Bosilovich, M. G., P. R. Houser, and S. D. Schubert, 1999: Interannual variability of the Mosaic Land-surface model. 2nd WCRP Conference on Reanalyses, August 1999, Reading UK.

Bosilovich, M. G., P. R. Houser, A. Molod and S. Nebuda, 1999: Comparison of FIFE observations with GEOS assimilated data including a heterogeneous land-surface model. 14th Conference on Hydrology, January 1999, Dallas, TX (also a poster presentation at the 1998 Fall AGU Meeting).

Bosilovich, M. G., W.-Y. Sun and J.-D. Chern, 1998: Numerical Simulation of the 1993 Midwestern Flood: Land - Atmosphere Interactions. GCIP Mississippi River Climate Conference, St. Louis, MO.

Bosilovich, M. G., R. Yang and P. Houser, 1998: Surface hydrology in global river basins in the Off-line Land-surface GEOS Assimilation system (OLGA). GCIP Mississippi River Climate Conference, St. Louis, MO.

Bosilovich, M. G. and W.-Y. Sun, 1997: Numerical Simulation of the 1993 Midwestern Flood: Influence of Local and Remote Evaporation 13th Conf on Hydrology, Febbruay 1997, Long Beach, CA.

Sun, W.-Y., and M. G. Bosilovich, 1997: Numerical Simulation of the 1993 Midwestern Flood: Model Verification. 8th Symposium on Global Change Studies, February 1997, Long Beach, CA.

Bosilovich, M. G. and W.-Y. Sun, 1994: Simulation of the PBL during the First ISLSCP Field Experiment (FIFE), 10th Conference on Numerical Weather Prediction, July 1994, Portland, OR.

PROFESSIONAL MEMBERSHIPS

American Meteorological Society and American Geophysical Union

AWARDS RECEIVED

January 1999 NASA Outstanding Performance Award (Code 910.3 Contractors)

Jeffrey P. Walker

Education:

Ph.D	1999	Department of Civil, Surveying and Environmental Engineering, The University of Newcastle, Australia
B.E. (Civil)	1995	Department of Civil, Surveying and Environmental Engineering, The University of Newcastle, Australia
B.Surv.	1995	Department of Civil, Surveying and Environmental Engineering, The University of Newcastle, Australia

Research Experience:

1999-present	Postdoctoral Research Fellow, USRA Visiting Scientists Program, NASA/GSFC, Greenbelt, Maryland, USA
1996-1999	Doctoral Scholar, Department of Civil, Surveying and Environmental Engineering, The University of Newcastle, Australia
1995	Honours Scholar, Department of Civil, Surveying and Environmental Engineering, The University of Newcastle, Australia

Awards and Honours:

1995	University Medal in Civil Engineering
	University Medal in Surveying
	The Deans' Medal
	The Tony Herzog Award
	The Peter Kleeman Medallion
	The Spruson & Ferguson Prize in Civil Engineering
	The Hunter Water Corporation Achievement Award
	The Institution of Engineers Australia Civil and Structural Branch Prize in Civil Engineering
	The Board of Surveyors' Medal
	The ACSE Prize in Structural Engineering
	The Consulting Surveyors New South Wales Prize in Land Studies
	The Institution of Surveyors Australia Hunter-Manning Group Prize in Surveying
	The James Hardie Pipelines Water Resources Engineering Prize
	Mine Subsidence Technological Society Prize in Geotechnical Design
	The Metal Building Manufacturers' Association Prize
1994	The SRIA University Award for Concrete Design
1993	The Astley Pulver Prize for Second Year Surveyors
1992	The BHP Rod & Bar Products Division Prize in Civil Engineering

Professional Affiliations:

Member, American Geophysical Union

Journal Papers:

Walker, J. P., Willgoose, G. R., and Kalma, J. D., 1999. Profile Soil Moisture Retrieval by Assimilation of Remote Sensing Observations. In preparation.

Walker, J. P. and Willgoose, G. R., 1999. Investigation of Cartometric and Photogrammetric Digital Elevation Model Accuracy. In preparation.

Walker, J. P. and Willgoose, G. R., 1999. On the Effect of Digital Elevation Model Accuracy on Hydrology and Geomorphology. *Water Resources Research*, 35(7): 2259-2268.

Conference Papers:

Walker, J. P., Willgoose, G. R. and Kalma, J. D., 1999. Recent Advances in Profile Soil Moisture Retrieval, *Water 99, 25th Hydrology and Water Resources Symposium*, Brisbane, 6 - 8 July 1999.

Walker, J. P., Willgoose, G. R. and Kalma, J. D., 1998. Towards Profile Soil Moisture Retrieval From Remote Sensing, *EOS, Transactions American Geophysical Union*,79(17): S41.
Walker, J. P., Troch, P. A., Mansini, M., Willgoose, G. R., and Kalma, J. D., 1997. Profile Soil Moisture Estimation Using the Modified IEM. In: *Proceedings International Geoscience and Remote Sensing Symposium (IGARSS)*, Singapore, 3 - 8 August, 1997, 1263-1265.

Reports:

Walker, J. P., 1999. *Estimating Soil Moisture Profile Dynamics From Near-Surface Soil Moisture Measurements and Standard Meteorological Data.* Dissertation Thesis, Department of Civil, Surveying and Environmental Engineering, The University of Newcastle.
Walker, J. P., 1995. *Accuracy of DEMs*. Honours Thesis, Department of Civil, Surveying and Environmental Engineering, The University of Newcastle.

Jared K. Entin

Raytheon ITSS
Hydrological Sciences Branch
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Education:

B.S. 1993, Meteorology; University of Michigan

M.S. 1996, Meteorology; University of Maryland
Scholarly Paper: Augmentation of Land Surface Modeling for Global Usage Through Comparison with Soil Moisture Observations

Ph.D. 1998, Meteorology; University of Maryland
Dissertation: Temporal and Spatial Scales of Soil Moisture Variations
Advisors: Alan Robock and Konstantin Vinnikov

Research and Teaching Experience:

Summer, 1992:	Research Assistant, Space Physics Research Laboratory University of Michigan
Sept. 1993 - Aug. 1994:	Assistant State Climatologist, State of Maryland
Sept. 1993 - Aug. 1998:	Graduate Research Assistant, Department of Meteorology, University of Maryland
Jan. - May 1998:	Teaching Assistant for Meteorology 200, Weather and Climate
Dec. 1998- Mar. 1999:	Post-doctoral Research Associate, Department of Environmental Sciences, Rutgers University
Mar. 1999 - present:	Scientist, Raytheon ITSS, Hydrological Science Branch, NASA Goddard

Computer Skills:

Operating systems: Unix (Dec and Sun), Windows 95, 98 & NT,
Languages: Fortran, html
Software: GrADS, XMGR, IDL, Microsoft Word & Excel

Publications:

Robock, A., K. Y. Vinnikov, J. K. Entin, and C. A. Schlosser, 1996: Evaluation of multi-year regional scale simulations of soil moisture, *Preprint Volume, Second International Conference on the Global Energy and Water Cycle* (GEWEX, Washington, DC), 39-40.

Vinnikov, K. Y., A. Robock, J. K. Entin, V. Zabelin, N. A. Speranskaya, and S. Liu, 1996: Regional scale variations of soil moisture, *Preprint Volume, Second International Conference on the Global Energy and Water Cycle* (GEWEX, Washington, DC), 176-177.

Robock, A., C. A. Schlosser, K. Y. Vinnikov, N. A. Speranskaya, J. K. Entin, S. Qiu, 1998: Evaluation of AMIP soil moisture simulations. *Global Planetary Change*, 19, 181-208.

Entin, J. K., A. Robock, K. Y. Vinnikov, V. Zabelin, S. Liu, A. Nahmkahi and Ts. Adyasuren, 1999: Evaluation of GSWP soil moisture simulations. *J. Meteorol. Soc. of Japan*, 77, 183-198.

Vinnikov, K. Y., A. Robock, S. Qiu, J. K. Entin, M. Owe, B. J. Choudhury, S. E. Hollinger, and E. G. Njoku 1999: Satellite remote sensing of soil moisture in Illinois, USA. *J. Geophys. Res, 104, 4145-4168*.

Vinnikov, K. Y., A. Robock, S. Qiu, J. K. Entin: Optimal Design of Surface Networks for Observation of Soil Moisture. In press, *J. Geophys. Res*.

Entin, J. K., K. Y. Vinnikov, A. Robock, S. Hollinger, S. Liu, A. Namkhai, and Ts. Adyasuren, 1999: Temporal and spatial scales of observed soil moisture variations in the extratropics. Sumitted to *J. Geophys. Res.*

Entin, J. K., A. Robock, S. Liu, and K. Y. Vinnikov, 1999: Temporal and spatial variations of soil moisture in China. In preparation for submission to *J. Hydroclimate*.

Presentations:

Robock, A., K. Y. Vinnikov, J. K. Entin, and N. A. Speranskaya. Soil moisture simulations for high latitudes compared to observations: improvements by considering water table and winter condensation effects. *EOS Supplement*, AGU 1994 Fall Meeting, 127. San Francisco, December 5-9, 1994.

Robock, A., K. Y. Vinnikov, N. A. Speranskaya, C. A. Schlosser, S. Liu, J. K. Entin, and V. Zabelin. Soil moisture observations: Ground truth (literally) for evaluation of remote sensing. XXI Scientific Assembly of the IUGG, Boulder, CO, July 2-14, 1995.

Entin, J. K., S. Liu, and A. Robock. Modeling Land Surface Processes in a Variety of Climates in China. Fall Meeting of the American Geophysical Union, San Francisco, Dec., 1995.

Robock, A., K. Y. Vinnikov, J. Entin, and N. A. Speranskaya. Soil moisture simulations for high latitude compared to observations: Improvements by considering water table and winter condensation effects. Spring Meeting of the American Geophysical Union, Baltimore, MD, May, 1996.

Robock, A., K. Y. Vinnikov, J. K. Entin, and C. A. Schlosser. Evaluation of multi-year regional scale simulations of soil. Second International Conference on the Global Energy and Water Cycle, Washington, DC, June 17-21, 1996.

Robock, A., K. Y. Vinnikov, J. K. Entin, V. Zabelin, N. A. Speranskaya, and S. Liu. Regional scale variations of soil moisture. Second International Conference on the Global Energy and Water Cycle, Washington, DC, June 17-21, 1996.

Robock, A., K. Y. Vinnikov, J. K. Entin, A. Schlosser, V. Zabelin, N. A. Speranskaya, and S. Liu. Modeling and remote sensing of regional scale soil moisture variations in Asia. Western Pacific Geophysics Meeting, Brisbane, Australia, July 23-27, 1996.

Robock, A., K. Y. Vinnikov, J. K. Entin, C. A. Schlosser, N. A. Speranskaya, V. Zabelin, and S. Liu. Soil moisture data set and its application. GCIP PI Workshop, Huntsville, AL, Nov. 19, 1996.

Robock, A., K. Y. Vinnikov, J. K. Entin, V. Zabelin, and S. Liu. Evaluation of Global Soil Wetness model calculations with observed soil moisture data 13th AMS Conference on Hydrology, Long Beach, CA, February 2-7, 1997.

Schlosser, C. A., A. Robock, A. J. Pitman, K. Y. Vinnikov, A. Slater, and J. K. Entin. Preliminary Results from PILPS Phase 2d: Analysis of Modeled Soil-Water and Snow Processes for an 18-Year Period at a Midlatitude Grassland Catchment. Spring Meeting of the American Geophysical Union, Baltimore, MD, May, 1997.

Vinnikov, K. Ya., A. Robock, J. Entin, and S. Qiu. Scales of soil moisture variability in remote sensing. GEWEX Continental-Scale International Project, Boulder, CO, Nov., 1997.

Entin, J. K., A. Robock, and K. Y. Vinnikov. Observed spatial and temporal scales of soil moisture variation in the extratropics. Fall Meeting of the American Geophysical Union, San Francisco, Dec., 1997

Robock, A., K. Y. Vinnikov, J. Entin, and A. Namkhai. The Mongolian soil moisture data set, and its application to observed trends and scales of soil moisture variations in Asia. Annual Meeting of the American Meteorological Society, Phoenix, AZ, Jan., 1998.

Entin, J. K., A. Robock, K. Y. Vinnikov, and P. Viterbo. Observed spatial and temporal scales of soil moisture variations in the extratropics. GEWEX Continental-Scale International Project Mississippi River Climate Conference, St. Louis, MO, Jun., 1998.

Vinnikov, K. Y., A. Robock., S. Qiu, and J. Entin. Optimal design of surface networks and remote sensing resolution. GEWEX Continental-Scale International Project Mississippi River Climate Conference, St. Louis, MO, Jun., 1998.

Robock, A., K. Y. Vinnikov, and J. Entin. Soil moisture data for the Mississippi river basin. GEWEX Continental-Scale International Project Mississippi River Climate Conference, St. Louis, MO, Jun., 1998.

Entin, J. K., A. Robock, K. Y., Vinnikov, and P. Viterbo. Evaluation of Global Soil Wetness Project soil moisture simulations and implications for land-surface modeling. Annual Meeting of American Meteorological Society, Dallas, TX, Jan., 1999.

Membership in Professional Societies:

American Geophysical Union

American Meteorological Society

Meteorology Student Association, University of Maryland
Chairperson, 1995-1998.

Certification of Compliance with the NASA Regulations Pursuant to Nondiscrimination in Federally Assisted Programs

The *NASA Goddard Space Flight Center (hereinafter called "Applicant ")* hereby agrees that it will comply with Title VI of the Civil Rights Act of 1964 (P.L. 88-352), Title IX of the Education Amendments of 1962 (20 U.S.C. 1680 et seq.), Section 504 of the Rehabilitation Act of 1973, as amended (29 U.S.C. 794), and the Age Discrimination Act of 1975 (42 U.S.C. 16101 et seq.), and all requirements imposed by or pursuant to the Regulation of the National Aeronautics and Space Administration (14 CFR Part 1250) (hereinafter called "NASA") issued pursuant to these laws, to the end that in accordance with these laws and regulations, no person in the United States shall, on the basis of race, color, national origin, sex, handicapped condition, or age be excluded from participation in, be denied the benefits of, or be otherwise subjected to discrimination under any program or activity for which the Applicant receives federal financial assistance from NASA; and hereby give assurance that it will immediately take any measure necessary to effectuate this agreement.

If any real property or structure thereon is provided or improved with the aid of federal financial assistance extended to the Applicant by NASA, this assurance shall obligate the Applicant, or in the case of any transfer of such property, any transferee, for the period during which the real property or structure is used for a purpose for which the federal financial assistance is extended or for another purpose involving the provision of similar services or benefits. If any personal property is so provided, this assurance shall obligate the Applicant for the period during which the federal financial assistance is extended to it by NASA.

This assurance is given in consideration of and for the purpose of obtaining any and all federal grants, loans, contracts, property, discounts, or other federal financial assistance extended after the date hereof to the Applicant by NASA, including installment payments after such date on account of applications for federal financial assistance which were approved before such date. The Applicant recognized and agrees that such federal financial assistance will be extended in reliance on the representations and agreements made in this assurance, and that the United States shall have the right to seek judicial enforcement of this assurance. This assurance is binding on the Applicant, its successors, transferees, and assignees, and the person or persons whose signatures appear below are authorized to sign on behalf of the Applicant.

NASA FORM 1206

NASA's Goddard Space Flight Center
Organization Name

Vincent V. Salomonson, Director of Earth Sciences
Name and Title of Authorized Representative

____

Signature | Date

CERTIFICATIONS, DISCLOSURES, AND ASSURANCES
REGARDING LOBBYING, AND DEBARMENT & SUSPENSION

1. LOBBYING

As required by Section 1352, Title 31 of the U.S. Code, and implemented at 14 CFR Part 1271, as defined at 14 CFR Subparts 1271.110 and 1260.117, with each submission that initiates agency consideration of such applicant for award of a Federal contract, grant, or cooperative agreement exceeding $ 100,000, the applicant must certify that:

(1) No Federal appropriated funds have been paid or will be paid, by or on behalf of the undersigned to any person for influencing or attempting to influence an officer or employee of an agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with the awarding of any Federal contract, the making of any Federal grant, the making of any Federal loan, the continuation, renewal, amendment, or modification of any Federal contract, grant, loan, or cooperative agreement.

(2) If any funds other than appropriated funds have been paid or will be paid to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with the Federal contract, grant, loan, or cooperative agreement, the undersigned shall complete and submit a Standard Form-LLL, "Disclosure Form to Report Lobbying," in accordance with its instructions.

(3) The undersigned shall require that the language of this certification be included in the award documents for all subawards at all tiers (including subcontracts, subgrants, and contracts under grants, loans, and cooperative agreements) and that all subrecipients shall certify and disclose accordingly.

2. GOVERNMENTWIDE DEBARMENT AND SUSPENSION

As required by Executive Order 12549, and implemented at 14 CFR 1260.510, for prospective participants in primary covered transactions, as defined at 14 CFR Subparts 1265.510 and 1260.117—

(1) The prospective primary participant certifies to the best of its knowledge and belief, that it and its principals:

(a) Are not presently debarred, suspended, proposed for debarment, declared ineligible, or voluntarily excluded by any Federal department or agency.

(b) Have not within a three-year period preceding this proposal been convicted of or had a civil judgment rendered against them for commission of fraud or a criminal offense in connection with obtaining, attempting to obtain, or performing a public (Federal, State or local) transaction or contract under a public transaction; violation of Federal or State antitrust statutes or commission of embezzlement, theft, forgery, bribery, falsification or destruction of records, making false statements, or receiving stolen property;

(c) Are not presently indicted for or otherwise criminally or civilly charged by a governmental entity (Federal, State or local) with commission of any of the offenses enumerated in paragraph (l)(b) of this certification; and

(d) Have not within a three-year period preceding this application/proposal had one or more public transactions (Federal, State or local) terminated for cause or default.

(2) Where the prospective primary participant is unable to certify to any of the statements in this certification, such prospective participant shall attach an explanation to this proposal.

NASA's Goddard Space Flight Center
Organization Name

Vincent V. Salomonson, Director of Earth Sciences
Name and Title of Authorized Representative

____

Signature   Date

A Global Land Data Assimilation Scheme (GLDAS)
Submitted to NRA-99-OES-04: *NASA-ESE Modeling and Data Analysis Research, EOS/IDS*

Paul R. Houser, Michael Bosilovich, Brian Cosgrove, Jared K. Entin, and Jeffrey Walker
NASA's Goddard Space Flight Center(GSFC), Hydrologic Sciences Branch; Greenbelt, MD 20771

Hua-Lu Pan and Kenneth Mitchell
NOAA's National Centers for Environmental Prediction(NCEP), Camp Springs, MD 20746

Concurrence

Paul R. Houser (PI) Hydrological Sciences Branch 301/614-5772	Date
Michael G. Bosilovich (Co-I) Hydrological Sciences Branch 301/614-6147	Date
Jeffrey Walker (Co-I) Hydrological Sciences Branch 301/614-5804	Date
Brian Cosgrove (Co-I) Hydrological Sciences Branch 301/614-5803	Date
Jared K. Entin (Co-I) Hydrological Sciences Branch 301/614-5825	Date
Edwin T. Engman Head, Hydrological Sciences Branch 301/614-5733	Date
Antonio J. Busalacchi Chief, Laboratory for Hydrospheric Processes 301/614-5671	Date
Vincent V. Salomonson Director of Earth Sciences 301/614-5635	Date

Proposal Cost Estimate (Not included in Proposal)

NASA-GSFC Annual Budget:	***Year 1***	***Year 2***	***Year 3***	***3 Year Total***
1. Personnel				
PI (Houser): 0.25 MY (U.S. CS)				
Co-I (Mitchell): 0.1 MY (U.S. CS)				
Co-I (Pan): 0.1 MY (U.S. CS)				
Co-I (Bosilovich): 0.1 MY (USRA)	$9,130	$9,587	$10,066	$28,782
Co-I (Walker): 0.1 MY (USRA)	$7,870	$8,264	$8,677	$24,810
Co-I (Entin): 0.1 MY (Raytheon)	$8,130	$8,537	$8,963	$25,630
Co-I (Cosgrove): 0.1 MY (GSC)	$6,670	$7,004	$7,354	$21,027
Contractor: 1.0 MY (NASA)	$79,840	$83,832	$88,024	$251,696
Contractor 1.0 MY (NOAA)	$79,840	$83,832	$88,024	$251,696
2. Communication and publication				
Publication charges	$5,000	$5,000	$8,000	$18,000
Supplies	$2,500	$2,500	$2,500	$7,500
Travel	$10,000	$10,000	$10,000	$30,000
3. Hardware				
Computer Hardware	$30,000	$15,000	$0	$45,000
Computer Maintenance	$5,000	$5,000	$5,000	$15,000
Computer Access	$0	$0	$0	$0
Data Purchase	$0	$0	$0	$0
Total GSFC Direct:	$243,980	$238,554	$236,607	$719,141
4. NASA-GSFC assessments:				
Branch assessment (3%)	$7,319	$7,157	$7,098	$21,574
Division assessment (3%)	$7,319	$7,157	$7,098	$21,574
GSFC Multiple Program Support Assessment:				
2.65 MY	$29,680	$32,993	$36,703	$99,375
1.0 PY MPS (not in budget)	$11,200	$12,450	$13,850	
Total GSFC Project Cost:	***$288,299***	***$285,860***	***$287,506***	***$861,664***